HARVARD ENGINEERING SCHOOL

Presented to
The Engineering Library
Pierce Hall
by A. E. Kennelly Oct. 4th 1906.

ELECTRICAL ENGINEERING

IN

THEORY AND PRACTICE

ELECTRICAL ENGINEERING

IN

THEORY AND PRACTICE

BY

G. D. ASPINALL PARR

M.Sc., M.I.E.E., A.M.I.Mech.E.

ASSOCIATE OF THE CENTRAL TECHNICAL COLLEGE, CITY AND GUILDS OF LONDON
HEAD OF THE ELECTRICAL ENGINEERING DEPARTMENT
THE UNIVERSITY, LEEDS

WITH 282 ILLUSTRATIONS

London

MACMILLAN AND CO., Limited

NEW YORK: THE MACMILLAN COMPANY

1906

PREFACE

THE rapid progress made in the past decade, and still taking place, in the application of pure science to industrial purposes, particularly electrical engineering, may be some excuse for presenting the present work to the technical world. In it a considerable departure has been made from other works of similar nature published up to the present. This will be evident by the inclusion of fundamental matter which, although elementary in nature, is important, and should be known by an electrical engineer; also from the order in which the subjects have been dealt with, and in which they may most profitably be read. Further, every endeavour has been made to produce a work which, while being fully up to date, excludes all historical matter and obsolete appliances, except in a very few cases where they embody important principles. Numerous references to current periodical technical literature have been made throughout the work, and all questions set for the Technological Examinations of the City and Guilds of London Institute, in the Preliminary, Ordinary, and Honours Grades of Electro-Technology up to date, are given at the end of the various chapters to the subject-matter of which they particularly relate.

The theory of the generation, transformation, and distribution of continuous and alternating currents, together with electrical machinery and other appliances most commonly met with in electrical engineering, will, at a later date, form an

addition to the present work, or will constitute the subject-matter of a second volume.

In conclusion, I wish to express my sincere thanks to the many manufacturing firms whose names appear in the text as makers of the various appliances, for the loan of blocks, and in some few instances for information relative to their manufactures.

I should also much appreciate any suggestions which would add to the educational value and usefulness of the work, and would be glad to receive intimation of any errors which may have escaped my notice in the proofs.

G. D. ASPINALL PARR.

THE UNIVERSITY,
LEEDS, *February* 1906.

CONTENTS

CHAPTER I

PAGE

Magnetism (Fundamental Principles) 1

CHAPTER II

Electricity (Statical)—Fundamental Phenomena . . 20

CHAPTER III

Electricity (Current)—Fundamental Principles and Units . 33

CHAPTER IV

Electrical Resistance 65

CHAPTER V

Electro-Magnetism 122

CHAPTER VI

Electro-Static and Electro-Magnetic Induction . . 167

CHAPTER VII

Electrical and Magnetic Instruments 204

CHAPTER VIII

PAGE
Electric Incandescent Lamps 295

CHAPTER IX

Electric Arc Lamps 345

CHAPTER X

The Production of Electro-Motive Force (Thermo-Generators —Primary Cells—Secondary Cells) 385

INDEX 441

CHAPTER I

Introduction.—In reviewing the progress of certain industries, it is impossible not to be struck with the almost phenomenally rapid development of that of electrical engineering. For the most part this is due to the somewhat rapid strides made in scientific discovery or research, particularly during the last twenty years, and which has resulted in new phenomena and ideas.

The electrical engineering industry is the outcome of the practical application of pure science in conjunction with mechanical engineering principles.

Innumerable instances of the rapid development of the industry may be seen in the various branches, namely, electric lighting, electric traction, electro-plating and the separation of the metals from their ores, also in telephony, ordinary telegraphy, and wireless telegraphy, the last-named being perhaps the most astonishing discovery of modern times.

It is principally with the first three branches mentioned above that we shall have to deal in the following pages, by considering the fundamental principles underlying the action as well as the construction of electrical apparatus and appliances in everyday use.

The author must be pardoned, in his desire for making this work as thoroughly up-to-date as possible, for omitting to consider many interesting appliances which have now fallen practically into disuse and belong more properly to the historical side of the subject. In excuse for so doing it will doubtless be sufficient to say that in a subject like electrical engineering, which is growing to such enormous proportions, it is impossible to do justice to a work of this nature with the limited space at one's disposal without omitting historical facts and confining ourselves solely to the subject as it is at the present time.

With these few introductory remarks we now pass on to the preliminary considerations of our subject.

MAGNETISM

Permanent Magnets.—These are employed in such a variety of different forms, and play so important a part in the construction and working of many important and widely used appliances at the present time, that it is desirable to consider the general properties and principal forms of permanent magnets, together with their relative advantages and disadvantages.

The permanent magnet of to-day originates from the discovery, made many centuries ago, of *natural permanent magnets*, subsequently termed *lodestones*, which are exceedingly rare and are found in small quantities in certain parts of the earth in the form of ore, termed by mineralogists *magnetite*, and having the chemical composition Fe_3O_4 (*i.e.* iron and oxygen in certain proportions).

Definition and Properties of a Magnet.—The question, however, may well be asked, *What is a magnet?* But to this no direct answer can be given other than that "a magnet is a material substance endowed with magnetism," while magnetism may in turn be defined as a phenomena which can only be judged by its effects and the properties exhibited by it.

A substance is said to possess magnetism, to be magnetic, or, briefly, to be a magnet, when it exhibits the following properties:—

1. Of attracting small pieces of iron, steel, etc.
2. Of attracting or repelling another so-called magnet.
3. Of pointing north and south when freely suspended by a thread.
4. Of magnetising other pieces of steel to form magnets.

The permanent magnets met with so commonly in practical work are, of course, artificially produced in a manner that will be described later on. Suffice it to say here that if a piece of iron or, better still, hard steel be rubbed or stroked with a magnet, it becomes magnetised, acquiring the same properties as the original magnet, or, in other words, those mentioned above.

Characteristics of a Magnet.—Let us now consider the action of

a flat, rectangular bar magnet NS (Fig. 1) on a piece of soft iron which is placed at different points along its length. If suitable means are employed to detect it, we shall notice that the force with which the soft iron is attracted to the magnet varies at different points. For instance, starting at the end N, the attraction is nearly a maximum, though not quite, at the extreme end, and can be represented in magnitude by the height of the ordinate NA. As we proceed towards the end S the attraction first increases to a maximum at some point B, and then decreases continuously to the centre O, at which it is zero. It then increases again continuously to a maximum at some point C, and finally decreases slightly to a value SD at the extreme end S. The ordinates between O and S are drawn *below* the magnet for reasons to be stated presently, but in all cases they represent the force of attraction at the different points along NS.

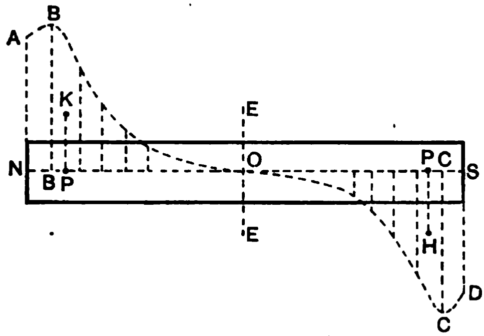


FIG. 1.—Curve of Distribution of Magnetism in a Bar Magnet.

On joining the tops of all these ordinates the curve ABOCD of *distribution* of magnetism in the bar magnet is obtained. From this it will be seen that the maximum magnetic effect, or greatest amount of free magnetism which is represented by the force of attraction, occurs at the ends of such a magnet, which are commonly called its *poles*. The line joining these poles through O is termed the *magnetic axis* of the magnet, and the line EOE the *neutral-axis*, *-zone*, or *equator* of it.

The poles of a magnet, however, are not coincident with its extreme ends, and may be assumed to be the points at which all the magnetism of the respective ends is concentrated. This is analogous to centre of gravity, which is assumed to be the point at which the whole weight of a body acts.

If K and H are the centres of gravity of the areas NABON and SDCOS respectively, then P, P, the projections of these points on to the magnetic axis, are the poles of the magnet.

Hence the actual length of a magnet is a little greater than the distance between its poles.

Polarity.—Now when a magnet is freely suspended, by a thread for instance, so as to be capable of oscillating in a horizontal plane,

it will come to rest with its magnetic axis lying nearly parallel to the line joining the north and south geographical poles of the earth. Further, the same end will always point in the same direction. For this reason the end which points towards the north geographical pole of the earth is termed the *north-seeking pole* of the magnet, and the other end, which points south, the *south-seeking pole* of the magnet.

These are briefly alluded to as the *north* and *south poles* of the magnet, and gives rise to the expression *polarity of a magnet.*

Mutual Action of Magnets.—By bringing a second magnet A near to the suspended one just mentioned, which we may call B, it will be observed that the north-seeking poles of A and B *repel* one another, as also do the south poles, but that the north pole of one *attracts* the south pole of the other. We therefore have the following important rules:—

1. *Like or similar magnetic poles repel one another.*
2. *Unlike or dissimilar magnetic poles attract one another.*

From the foregoing remarks there appears to be two opposite kinds of magnetism—north and south, resident at and near the poles of any magnet. Moreover, it is impossible to have only one kind present, *i.e.* a magnet with only one pole; for if a magnet is broken into two parts, each part will still have two poles of opposite kinds.

The Earth a Magnet.—The action of a freely suspended magnet in setting itself north and south, coupled with the fact that it does so at various parts of the earth's surface, clearly indicates that the earth must possess a distinct magnetic north and south pole: in other words, that the earth is a huge magnet. It has, however, been proved by experiment that the north magnetic and geographical poles do not coincide, as also the south poles, being some 1000 miles or so apart. From what was said above with regard to the mutual action of two magnets, it follows that the north-seeking pole of our suspended magnet is actually the south pole, since it is attracted towards the north magnetic pole of the earth, and similarly for the south; but to avoid confusion we will retain the terms "north-seeking" and "south-seeking" to denote the poles of a magnet marked with an N and S at its ends.

Magnetic Substances.—It is important to note the difference between permanent magnets and magnetisable substances. The latter include all kinds of *iron* and *steel*, *nickel*, *cobalt*, *manganese*, *chromium*, *cerium*, *salts of iron*, and a few other substances. Of these, only nickel and cobalt are at all comparable with iron and steel, which are the best and most easily magnetisable of all.

All these substances retain *some* magnetism after being magnetised,

but in most cases extremely little. Hard steel is the only one that retains the greater part of the magnetism imparted to it, giving rise to the term *permanent* magnet. Soft iron retains very little magnetism, *i.e.* it is only capable of acting as a *temporary* magnet while under the influence of a permanent one, but it is, at the same time, a highly magnetisable substance.

Lines of Magnetic Force.—If a flat, stiff sheet of cardboard is laid horizontally over a magnet and soft iron filings sifted fairly uniformly over it, then on gently tapping the cardboard a few times the filings will be found to arrange themselves (in the case of a simple bar magnet NS) in a system of curves represented approximately in Fig. 2. The position of these curves shows the direction along

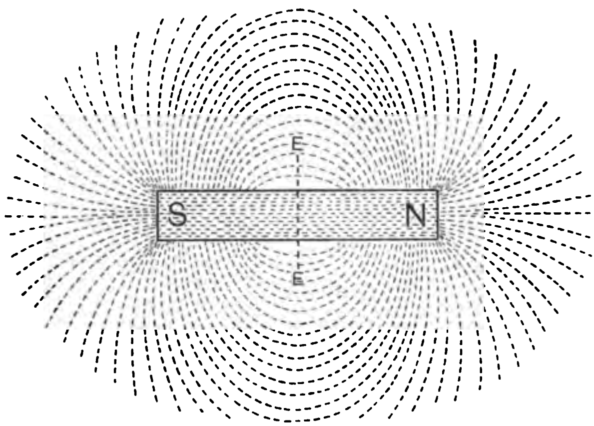


FIG. 2.—Lines of Magnetic Force due to a Bar Magnet.

which the *magnetic force* acts, while the denseness of them at any point indicates the intensity of this force.

They are therefore called *lines of magnetic force*, or *lines of force* simply. It will be noticed that they all pass through the central portion or equator EE of the magnet, but begin to emerge from the sides of the magnet as we approach the ends on either side of EE.

By far the greater number of them, however, pass through the interior of the magnet and emerge from the ends as indicated. Each line of force is continuous in itself, and completes its path in the air or other matter outside NS. The path of some of the lines is very short, while of others it is very long, as, for instance, in the case of some of those emanating from the extreme ends of NS.

Now, whenever lines of force emanate from a magnetic body and pass into the air, that body is said to possess *free magnetism.* In the

case of Fig. 2 the magnetism is *all free*, and therefore available for producing a force of attraction or repulsion on any magnetic material.

Magnetic Field.—The lines of force emerging from NS in Fig. 2 are those in the plane of the cardboard, but if the magnet is fixed in an upright position, and filings sifted on to the cardboard while it is resting on the upper end of NS, it will be noticed that the lines emerge from the pole radially in all directions and return to the other pole in a similar manner. In other words, the magnet is completely enveloped by the lines of force which emerge from it on one side of EE and re-enter at the other, completing their path in the surrounding space, which is commonly called the *magnetic field* of the magnet.

Hence a magnetic field exists wherever there is free magnetism, or wherever the filings place themselves. For convenience it is universally assumed that the lines of force emanate from the magnet on its N side into the air, through which they flow, finally entering the magnet again on the S side of EE.

It is interesting and instructive to note the distribution of magnetic field due to two similar and dissimilar magnetic poles in the vicinity of one another. In Fig. 3 is indicated approximately that due to unlike poles when near one another.

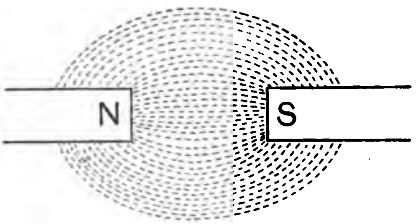


FIG. 3.—Attraction of Unlike Magnetic Fields.

It would appear from this as if the lines attract one another and alter their respective paths so that their coalescence may be a maximum. Fig. 4 shows the distribution of field in the case of two similar poles S or N, and here it will appear that the respective fields repel one another; for, from what has been previously said, the lines of force are emerging from each of the N poles in opposite directions.

If an ordinary bar magnet be bent round into the shape of a U, the distribution of field will approximate closely to that shown in Fig. 5. In this case, in obedience to the universal rule that *lines of force take the path of least obstruction or resistance*, they will flow from pole to pole across the top of the U. Most of those near the neutral region EE will flow *between* the limbs, though some will complete their path from the outside of the left-hand limb under the bend and in at the outside of the right-hand limb.

Now, if a piece of magnetic material such as, for instance, soft iron be placed near a permanent magnet, the normal distribution of the field is altered to an extent depending on the proximity of the iron.

Many of the lines of force in the neighbourhood alter their path in order to try and pass through the iron, which offers far less resistance to their passage than does the air.

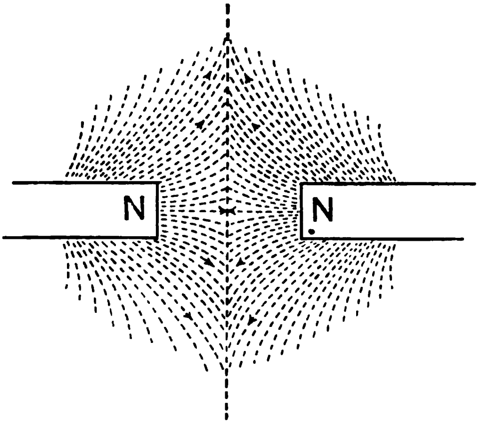


FIG. 4.—Repulsion of Like Magnetic Fields.

This is indicated in Fig. 6, which represents a U-shaped magnet with a soft iron armature or keeper A, as it is often called, fixed independently between its poles. In this case it will be noticed that the lines crowd up to and emerge from the N pole, pass through the armature A, and into the S pole. The effect of A is to concentrate and direct the field between the poles, and also to prevent many of the lines of Fig. 5 from passing between the lower portions of the limbs and out from the outside of them.

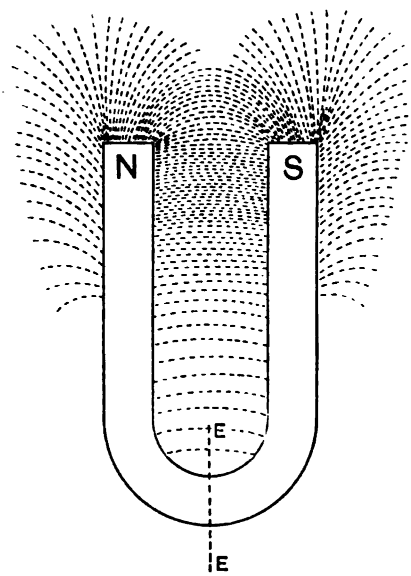


FIG. 5.—Magnetic Field of a U Magnet.

Fig. 6 represents the permanent magnetic portion of a well-known and widely used kind of instrument, and the principle therefore of it is of great importance. Referring to Fig. 5, as the ends of the limbs are brought closer together, the magnetic field becomes more intense between the poles or ends owing to the diminution of resistance in their path decreasing at this point. This is the case of the so-called *horse-shoe magnet*, now so commonly met with, as a toy, at the present day. The effect of placing a piece of soft iron (the keeper) near its poles or across them is also so well known as hardly to need mentioning. The very strong force of attraction which results is solely due to the lines of force crowding

into the keeper so as to find a path of smaller resistance than across the air between the poles, and to their endeavour to shorten that path as much as possible; both these ends being attained when the armature or keeper is up against or across the poles. It will be noticed that the force of attraction is not nearly so great between one pole of a simple bar magnet (Fig. 2) and the iron keeper, because fewer lines of force enter the latter. We shall, however, come to this point again in connection with the force of attraction of a magnet.

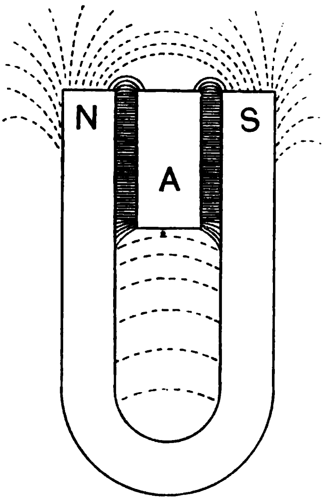


FIG. 6.—Magnetic Field of a U Magnet, with Armature.

Magnetic Induction.—As the term implies, magnetic induction is the phenomenon of *inducing* magnetism in magnetic material by the *influence, from a distance*, of another magnet on it. The effect is one of great importance, since most of the instruments used in electrical engineering are liable to this inducing effect from outside sources, which may, unless care is taken, cause grave errors in their indications. Magnetic induction takes place in any magnetisable substance which is sufficiently near to a magnetic field for some of the lines of force to pass through the substance. Moreover, N and S polarity is always set up, and, knowing the direction of the field, we can always predict that *induced* in the substance, for an *S pole will always be formed at the part where the lines of force enter the substance,* and an N pole where they leave it, no matter what its shape may be. In other words, the pole nearest to that of the inducing magnet will be of opposite kind. The substance so influenced is able to, and does, act as a magnet during the time for which the magnet acts on it, but in most cases loses its magnetism after the magnet is removed. The reason for a magnet attracting a piece of iron which has not been previously magnetised lies in the fact that polarity is first induced in the iron, and then attraction ensues from the fact that unlike poles attract with a force in excess of that with which the like poles repel.

Magnetic Screening.—The preceding remarks lead us to what is, at the present day, a most important precaution which is used in ships' compasses and many measuring instruments. Magnetic induction takes place across every known substance *except* those which are *magnetisable*

to a considerable degree. Consequently such instruments as are affected by external magnetic fields can be protected from them by placing a sheet of magnetisable material, which we may term a *magnetic screen*, between them and the fields. Good soft wrought-iron or mild steel are the best materials to use for such screens. The screening action will be easily understood by reference to Figs. 7 and 8.

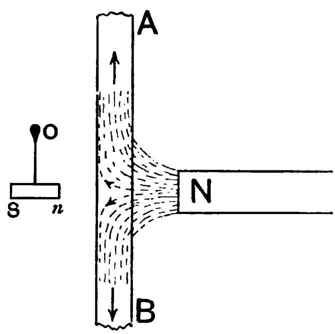


FIG. 7. Magnetic Screening Effect of an Iron Plate.

In the former, the north pole N (say) of a magnet is placed near a suspended magnet *ns*, with an iron screen AB between. If AB is both thick and large enough, the lines of force will enter it and try to continue their path wholly in AB, with the result that *ns* is entirely unaffected by this neighbouring magnetic field, there being *no free magnetism* pervading the space in which the field of *ns* acts. A more certain screening action would be obtained with an arrangement such as that shown in Fig. 8, in which the freely suspended magnet *ns* is enclosed in a soft iron or mild cast-steel cylinder AB, having preferably the back and part of the front of the same material. The dotted arrow lines show the path which the lines of force take, due to some outside field NS.

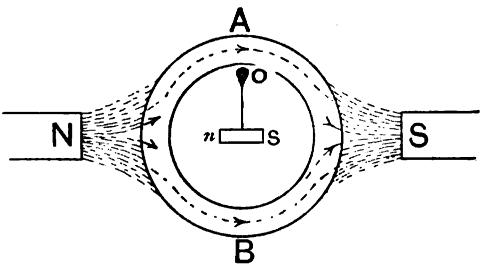


FIG. 8.—Magnetic Screening by an Iron Cylinder.

If the thickness of the walls of AB is such as to offer a sufficient conducting path for the lines, these latter will flow wholly in the iron case, without emerging into the interior. If, in addition, the back and front is also of the same material, some of the lines will flow through them also; but in all cases, so long as the external field is unable to exhibit free magnetism inside, there will be no effect on any magnetic device placed in the interior.

This arrangement is now being largely used for shielding ships' compasses and delicate electrical engineering instruments from the powerful magnetic fields in which they often have to be fixed, a small window closed with glass being left in the front end to read the indications of the instruments. It should be remembered, however, that the

efficacy of any screening device diminishes as the material of the screen becomes more nearly saturated (p. 13), so that the induction density (p. 18) in magnetic screens should always be fairly low. Furthermore, the screening effect in alternating current fields increases with the rapidity of alternation.

Strength of Magnets.—This is *measured by the magnetic force exerted by either pole* of any magnet, for the strength of a magnet is represented by the strength of its poles.

Since, however, we have seen that magnetic force acts only where free magnetism exists, or, in other words, only in a region pervaded by magnetic lines of force, it is evident that the *strength of a pole is the amount of free magnetism at that pole.*

Consequently, if the number of lines of force emerging from the N or S pole of a magnet A were double the number emerging from the N or S pole of a magnet B, then the strength of magnet A would be said to be double that of B.

Experiment tends to show that the magnetisation over the whole area of cross section of a magnet is by no means uniform; or, if we imagine the magnet to be built up of thin strata of steel, the outermost stratum or surface is the most highly magnetised, while each succeeding stratum—or layer of magnetism, if we may be allowed the expression—as we proceed from the surface, becomes less and less strong. Consequently long thin steel magnets are more powerful in proportion to their weight than thicker ones, and there is evidently no advantage to be gained by employing thick solid steel magnets when *strong* permanent ones are required.

Where maximum strength is required, magnets are built up of comparatively thin laminæ of good hard steel, either in the form of strips, horse-shoes, U's, or any other desired shape, separately magnetised as strongly as possible, and afterwards assembled together side by side to the desired size, with *like poles* together.

The *compound* or *laminated magnet* so formed is found to be stronger than a solid one of equal dimensions and weight in the same material, though a little weaker than the sum of the strengths of its component parts. Such magnets are used for many purposes, one instance being the familiar D'Arsonval galvanometer (p. 211) and other similar permanent-magnet instruments. The best steel to employ for constructing permanent magnets is that known commercially as 'Allevard' steel, and also that made at *Haarlem.* A. Abt[1] finds that magnets made of Wolfram steel are about twice as strong as any other kind

[1] *Wied. Annalen,* 66. 1, pp. 116-120, 1898.

initially, other conditions being the same, but that they lose their magnetism more rapidly.

Molecular Theory of Magnetism.—It has already been mentioned that if a magnet be broken up into a number of tiny pieces, each will still be a magnet having an N and S pole.

Extending this to the limit by breaking it up into its constituent molecules (*i.e.* the smallest particles of this or any other substance that can exist in a free state), each molecule will be a magnet having a definite N and S pole. This leads us to the now generally accepted theory of magnetism, namely, the *molecular* one, according to which every molecule of any magnetisable material possesses a perfectly constant magnetic N and S polarity. When such material exhibits no *free magnetism*, even though it may be in the form of a bar or horse-shoe magnet, we are accustomed to say it is unmagnetised. In reality, however, the magnetised molecules are so arranged or mixed up internally as to form closed magnetic circuits amongst themselves, and in this condition no lines of force emerge into the air.

During the process of magnetising the material, when the lines of force from an outside magnetic source pass through it, the magnetised molecules turn so that their N poles all point one way, *i.e.* in the direction of the lines of force, and in more or less straight lines.

The material is then said to be *polarised*, with the result that a free N pole is produced at one end of the material and a free S pole at the other. From the foregoing it would appear that the maximum limit of magnetisation is reached when *all* the molecules are end on to one another and arranged in straight parallel rows. Careful researches on magnetism by Hughes, Beetz, and others tend to substantiate this theory, as also the fact that on magnetising a glass tube full of iron filings they set themselves end on to one another, and so continue to exhibit magnetism until shaken up. Again, vibration during magnetisation accelerates and improves the action, tending to show that the molecules are helped into position mechanically as well as magnetically. The above remarks lead us to the following important consideration.

Magnetic Retentivity.—The foregoing theory supplies us with a highly probable reason why all magnetisable substances do not become magnetic permanently, or why one will exhibit more magnetism than another after the removal of the magnetising influence. As a general rule, the harder the substance the more permanent is its magnetism, the more difficult it is to magnetise or get rid of the magnetism when once properly acquired. In explanation of this, the molecules of the softer material may be supposed to be much more loosely packed together than those of harder material; hence, when the magnetising

influence is removed, they wholly or partially collapse amongst themselves, turning out of the uni-directional straight lines into all kinds of positions, thus completing their magnetic circuits through themselves and nearly eliminating all free magnetism.

Substances which behave in this way are *cast*-iron, cobalt, impure qualities of wrought-iron, certain kinds of mild steel, and particularly soft annealed Swedish charcoal iron and pure soft iron. On the other hand, in the case of hard materials such as lodestone, steel, nickel, the molecules when once set so as to exhibit free magnetism remain set, for the most part, from an apparently greater difficulty in moving due to being packed more tightly, thus giving rise to a considerable amount of *free* or permanent magnetism.

These latter materials therefore retain the greater part of the magnetism imparted to them. In other words, their *retentivity* or the *residual magnetism*—*i.e.* what remains after the magnetising force is removed—is high; but the ability of any substance to exhibit this property depends entirely on its chemical composition and molecular structure. A steel bar is much more difficult to magnetise than an iron one of the same dimensions, but its retentivity is much greater, and this illustrates a general rule for most magnetisable substances. The resistance or force opposing the motion of the molecules, and therefore which opposes magnetisation or demagnetisation, has been termed *coercive force*; but this is not a happy term to use for *this* property, *retentivity* being preferable and more expressive.

Tractive Force of Magnets.—The tractive force, lifting power, or portative force of a magnet, as it is variously termed, depends on—(1) the form of magnet, (2) shape of attractive surfaces and how well they fit, (3) strength of the pole or poles, (4) area of contact surface, (5) how the load is applied, (6) shape and size of armature attracted across the poles.

As will be gathered from the remarks on page 10, a small magnet will lift a greater load in proportion to its own weight than a large magnet. The force of attraction between any magnet and its armature is directly proportional to the intensity of the magnetisation induced in the latter, providing the armature, by reason of its mass and high intensity, does not react on the magnet, altering the strength of the latter. Further, if the magnet and armature are uniformly magnetised throughout their mass of cross section, the force of attraction will be proportional to the cross section of the iron.

Now, in order to increase the tractive force of any magnet and make it a maximum, as many lines of magnetic force must be made to pass through the armature as possible.

To ensure this, the armature should be made of the softest iron, as short as possible, and with sufficient cross section throughout to carry the lines of force.

It should be remembered that air offers some hundreds of times greater resistance to the passage of the lines of force than soft iron does. Hence the necessity for carefully facing the contact surfaces between magnet pole and armature in order to diminish the air film between them when in contact, which tends to prevent some of the lines entering the armature. To still further counteract the effect and diminish the effective resistance of this minute air film, the area of contact may be increased with advantage.

The best form of magnet to employ is the horse-shoe, where both poles attract the same armature; and since the intensity of magnetisation of the latter, which is proportional to the tractive force, is also directly proportional to the strength of the magnet, this latter should be as strong as possible and therefore laminated. Such a magnet will lift a load four or five times as great as a bar magnet, of equal weight, will lift. Generally speaking, a good horse-shoe permanent steel magnet, in which attention has been paid to the foregoing remarks, should be capable of lifting a load of some twenty-five times its own weight. It has been found, however, that if the load on a magnet be gradually increased day by day, it will finally support a much larger one than it could have done if the load had been suddenly applied. This behaviour so far has not been explained, but in all cases it only lasts until the increased load detaches the armature, when the magnet apparently resumes its usual power of attraction.

Magnetic Saturation.—On page 11, in connection with the molecular theory of magnetism, it was mentioned that the maximum limit of magnetisation would be reached when all the molecules assumed the end-on position, forming parallel lines.

A magnetisable substance in this condition, or, which is the same thing, one that has been magnetised so strongly as to be incapable of, so to speak, absorbing or allowing any more lines of magnetic force to pass through it, is said to be magnetically *saturated*. No magnet remains saturated, or is even able to maintain the high degree of magnetisation excited, after the magnetising force is removed, though most magnets are stronger immediately after than some time after. It is curious to note the effect of heat on the magnetisation of magnetic materials. Increase of temperature decreases the strength of a magnet, and it is possible, in most cases, to eliminate the magnetism by heating the magnet to red heat, or even less, but it recovers partially on cooling. Cooling, within limits, increases the strength

of a magnet. Further, it is very important to remember that mechanical vibration tends to eliminate free magnetism, the molecules appearing to be jarred out of their end-on position.

In the case of *permanent steel magnets*, it is therefore very *injurious to knock* or *drop them about*, while for some appliances it is even advantageous to have vibration.

A permanent steel magnet may in the long-run be magnetised more strongly by gently jarring it while being magnetised by certain methods.

Magnetic Permeability or Inductivity.—We have more than once spoken of the obstruction or resistance to the passage of magnetic lines of force, and the reader will have gathered that all substances or matter do not conduct lines of force with equal facility. The conducting power, of any substance or medium, for lines of magnetic force may be termed its *magnetic conductance*, and the reciprocal of this, its *magnetic resistance*. The *specific magnetic resistance* of any medium is the magnetic resistance offered by a unit cube of the medium, and is often denoted by the Greek letter ρ. The reciprocal quality to specific magnetic resistance is called *magnetic permeability* or inductivity, and is generally represented by the Greek letter μ.

Hence
$$\mu = \frac{1}{\rho},$$

and the magnetic permeability of any medium is the magnetic conductance of the magnetic circuit composed of this medium of unit length and unit section. μ is a *constant* of definite value for any given medium; it is always positive, and is taken as unity for empty space (vacuum). For air, zinc, mercury, lead, silver, copper, gold, water, and a few other substances it is *slightly less than* 1.

For magnetic materials, *e.g.* iron, steel, nickel, cobalt, manganese, and many compounds of these, μ is greater than 1. It is, however, greater for soft iron than for other substances, and may reach 3600, but for steel may only be about 800. In other words, the magnetic resistance offered by steel may be from four to five times that offered by good soft iron.

Laws of Magnetic Repulsion and Attraction.—There are two important fundamental laws of magnetic force:—

1. *That like magnetic poles repel, and unlike magnetic poles attract one another.*

2. *That the force exerted between two magnetic poles is proportional to the product of their strength, and inversely proportional to the square of the distance between them.*

The first law we have already dwelt upon sufficiently, and the second we will now consider. If m_1, m_2 are the strengths of any two magnetic poles, and d the distance between them, then the force F of attraction or repulsion, depending on whether they are unlike or similar poles, will be

$$F \propto \frac{m_1 m_2}{d^2};$$

and further, if μ is the magnetic permeability of the surrounding medium, then

$$F = \frac{1}{\mu} \times \frac{m_1 m_2}{d^2} = \rho \times \frac{m_1 m_2}{d^2}.$$

Now μ for air is so very nearly 1 that in practice it is always taken as 1; and if $d = 1$ centimetre and $F = 1$ dyne (for definition of which *vide* page 60), we obtain the definition of a magnetic pole of unit strength.

Thus: *A magnetic pole of unit strength is one such that, when placed at a distance of one centimetre from a similar pole of equal strength, repels it with a force of one dyne.*

Examples will aid the reader to understand the application of the above law more thoroughly.

Example 1.—What force would a magnet pole, the strength of which is 4 units, exert upon another pole of strength 8 units placed 2 centimetres away? Assuming the permeability of the surrounding medium unity, then substituting in the above relation, namely—

$$F = \frac{1}{\mu} \cdot \frac{m_1 m_2}{d^2},$$

we have
$$F = \frac{1}{1} \cdot \frac{4 \times 8}{(2)^2} = \frac{32}{4} = 8 \text{ dynes.}$$

It is, of course, at once known whether this force is one of attraction or repulsion, if the polarity is known, since like poles repel, and unlike ones attract, one another.

Example 2.—A magnetic pole of strength 10 units acts with a force of 20 dynes upon another pole placed 5 centimetres off. What is the strength of this pole?

Here let $m_1 = 10$ and $\mu = 1$. Then m_2 is found thus:—

Since
$$F = \frac{1}{\mu} \cdot \frac{m_1 m_2}{d^2},$$

∴ the required pole strength $m_2 = \frac{F \mu d^2}{m_1} = \frac{20 \,.\, 1 \,.\, (5)^2}{10} = \frac{20 \times 25}{10} = 50$ units.

Example 3.—A magnetic pole of strength 5 units acts with a force of 25 dynes on another pole of strength 20 units. What is the distance between them?

Here $$d^2=\frac{m_1 m_2}{F\mu} \text{ or } d=\sqrt{\frac{m_1 m_2}{F\mu}},$$

$\therefore$ the required distance $$d=\sqrt{\frac{5\times 20}{25\times 1}}=\sqrt{4}=2 \text{ cms.}$$

Magnetic Moment of a Magnet.—From what has just been said it is evident that the force f acting on a magnetic pole of strength m in a magnetic field of intensity H will be

$$f=m\,.\,\mathrm{H}.$$

But since it is impossible to have only one pole without another of opposite kind, we have to consider the combined action of the two poles N and S in the field. If we suppose the magnet to be freely suspended, both poles will be acted on by the field equally and in the same sense. Hence we shall have two equal and opposite parallel forces $\mathrm{H}\times m$ acting on the poles of the suspended magnet in the field H, tending to turn it so that both fields coalesce. If $l=$ distance between the poles, *i.e.* length of magnet nearly, the forces $m\mathrm{H}$ at the ends of l form a *couple*, as it is termed in mechanics, and the total force acting on the magnet will be

$$f_1=lm\mathrm{H}.$$

The product ml is called the *magnetic moment* of the magnet.

Intensity of Magnetisation.—We have seen that the strength of a magnet depends upon its *size*, *shape*, and material of which it is made, and also on the magnetising force employed in making it a magnet. It becomes therefore a matter of difficulty to compare the usefulness of any two magnets. The way in which it is usually done is based on the assumption that the magnet is *uniformly magnetised*, *i.e.* that the magnetism is uniformly distributed over the cross section at right angles to the magnetic axis, which, as we have already seen, is not the case with thick magnets. Further, that the poles are coincident with its ends, which also is only true for fairly long thin magnets.

Assuming these two points, any two magnets may be compared by their respective intensities of magnetisation, I. For

$$\mathrm{I}=\frac{\text{magnetic moment}}{\text{volume of magnet}}=\frac{ml}{a.l}=\frac{m}{a},$$

where $a=$ sectional area of magnet.

In other words, their magnetic moments per unit volume are compared. An example may make this clearer.

Example.—Two rectangular bar magnets have poles of the same strength, but one (A) is $12''$ long and $1''\times\frac{1}{2}''$ in section, the other

(B) is 24″ long and 2″ × 1″ in section. What are their relative intensities of magnetisation and relative magnetic moments ?

From the above relation we have

$$I_A = \frac{ml}{al} = \frac{m}{a} = \frac{m}{(1 \times \frac{1}{2})} = 2m$$

and

$$I_B = \frac{ml}{al} = \frac{m}{a} = \frac{m}{(2 \times 1)} = \frac{m}{2};$$

$$\therefore \qquad \frac{I_A}{I_B} = \frac{2m}{m/2} = \frac{2 \times 2 \times m}{m} = 4,$$

or the intensity of magnetisation of A is 4 times that of B.

Again, if we denote the magnetic moments of the two magnets by the letter M with suffix A or B, we see that

$$\frac{M_A}{M_B} = \frac{ml_A}{ml_B} = \frac{12}{24} = \frac{1}{2},$$

their strengths of poles being equal. Hence the magnetic moment of B is twice that of A.

Lines emanating from Unit Magnetic Pole.—Suppose a single magnetic pole of strength m to occupy a position in space away from any other magnetic field, and to have described around it an infinitely thin spherical surface at a radius r and with the pole as centre, then the intensity of the magnetic field at any point on the surface at distance r from the pole and due to it, in other words, the number of lines cutting unit area of the spherical surface, $= \frac{m}{r^2}$, and the area of the whole spherical surface $= 4\pi r^2$.

Whence the total number of lines cutting it or emanating from the pole $= 4\pi r^2 \times m/r^2 = 4\pi m$.

$\therefore$ *a unit magnetic pole will have* 4π *lines of magnetic force emerging from it.*

Magnetic Induction.—If a long thin rod of iron or other magnetic material be placed in a uniform magnetic field of intensity H in air, with its length parallel to the lines of force of the field, then the total number of lines of force crossing unit area of the end of the rod $= H \times 4\pi \frac{m}{a} = H + 4\pi I$, where

I = intensity of magnetisation at the end of the rod $= \frac{m}{a}$,
m = strength or number of lines due to the induced pole,
a = cross sectional area of the rod.

The above summational term is commonly denoted by B, so that

$$\mathbf{B = H + 4\pi I};$$

also

$$B = \mu . H,$$

or

$$\mu = B/H,$$

which is one of the most important fundamental laws in magnetism.

The induction density B is therefore defined as the number of lines of magnetic force passing through unit area of cross section, in practice taken as a square centimetre or square inch. In the best soft wrought-iron B may be as high as 20,000 for high magnetising forces, while in steel it seldom exceeds 10,000, and is more often about 7000. Good permanent steel magnets may be magnetised to a permanent induction of about 8000 or 9000 magnetic lines of force per square centimetre. The *total* number (N) of lines of force passing through the neutral region of a magnet is of course

$$N = B \cdot a,$$

and this is sometimes called the *total field*, *flux*, or 'total induction,' or even 'induction' simply; but the last two terms are likely to be misleading, and should be avoided, since they are likely to be confused with the induction density B per unit area. The terms 'flux' or 'total field' for the above expression of N are therefore to be recommended. An example or two will help to familiarise the reader with the difference.

Example 1.—A flux of 100,000 lines of magnetic force are passing through a magnet, the size of which = 5 inches × 2, what is the induction density?

Since $$N = B \cdot a,$$

∴ the required induction density $B = \frac{N}{a} = \frac{100000}{2 \times 5} = 10{,}000$ lines per square inch.

Example 2.—If the induction density in the above magnet had been 5000 lines per square inch, find the total field. Total field (flux) = $B.a = 5000 \times 2 \times 5 = 50{,}000$ lines.

The reader has now been acquainted with many fundamental facts and definitions of great importance, and he should endeavour to make himself familiar with them, as he will find that they have to be continually brought up in connection with much that has yet to be dealt with.

QUESTIONS ON CHAPTER I

[*Supplement all Answers with Sketches when possible.*]

1. Distinguish between a *magnet* and *magnetic substance*, and enumerate the various properties of each.

2. What is meant by '*free magnetism*'? Explain its connection with the force exerted by the magnet, and how this latter varies in (1) a bar magnet, (2) a U-shaped magnet.

3. Explain the terms '*magnetic field*,' '*magnetic axis*,' '*neutral region*,' '*polarity*,' '*lines of magnetic force*,' in connection with magnets in general.

4. State the laws of mutual action between magnets.

5. What is the effect of bringing a piece of iron near the poles of a magnet? Can the effect be made use of in any way?

6. What do you mean by the strength of a magnet? How can it be increased?

7. Give a short account of the *molecular theory of magnetism*, pointing out its weak points.

8. Carefully define the terms Magnetic -Retentivity, -Saturation, -Permeability, -Inductivity, -Induction, and -Flux.

9. On what does the 'tractive' force of a magnet depend, and how can it be increased?

10. What do you understand by the '*intensity*' *of magnetisation*, '*magnetic moment*,' and '*unit pole*'?

11. Two magnetic poles, the strengths of which are 8 and 16 units respectively, are placed 4 cms. apart, what is the force exerted between them?

12. Find the strength of a magnetic pole which acts with a force of 40 dynes on another pole, of strength 20 units when placed 10 cms. away from it.

13. What is the distance between two poles which act on one another with a force of 50 dynes, if their strengths are 60 and 10 units respectively?

14. The magnetic flux through a rectangular bar magnet $1'' \times 2''$, in section, is 20,000 lines. Find the permeability of the material of the bar if the magnetising force $= 10$.

15. Compare the intensities of magnetisation of two bar magnets, one of which is 6″ long and 1″ diameter, the other 9″ long and 2″ diameter, their pole strengths being respectively 40 and 60 units.

16. Compare the relative magnetic moments of the two magnets mentioned in question 15.

17. Write an account of the method of making magnets so that they may be permanent. Explain what sort of variation you would expect to find in a good magnet belonging to some measuring instrument. (Hons. Sect. I. 1898.)

ELECTRICITY (STATICAL)

CHAPTER II

FUNDAMENTAL PHENOMENA

Electricity—Its Nature.—It is not uncommon to sometimes meet with phenomena which cannot be explained. Theories may be advanced to account for certain well-known facts connected with them which common sense tells us might very probably be the case. What electricity is has not yet been satisfactorily determined, but more than one theory has been propounded to explain its nature. Unlike sound, light, and heat, however, electricity is not in itself a form of energy; and it is certainly not a form of matter. Electrification is, however, accompanied by the production of energy, and results from the expenditure of energy whether chemical, mechanical, or otherwise. Without committing ourselves to any theory which may actually be unjustifiable, we will be content to judge of what we commonly term *electricity* by its effects.

Electrical Attraction and Repulsion.—If a glass rod, which has been well dried, be rubbed with a dry silk cloth and held near to small pieces of cork, pith, sawdust, paper, or cut straw, etc., these will at once move towards the rod, some of them sticking to it while others move rapidly away after touching it, as if repelled by the rod. Moreover, a tiny spark passes between the rod and finger when the latter is held close to it, and is accompanied by a crackling noise. In ordinary parlance, the rod is said to be *electrified* when it exhibits such peculiar properties, which it did not previously possess, apparently the result of the rubbing. The name *electricity* is given to the agent to which such phenomena as the above are ascribed.

Two Kinds of Electrification.—When a glass rod that has been rubbed with a silk pad is held near to a pith ball suspended by a dry silk thread from a support, the pith ball is attracted and flies

towards the rod. Having touched it, the ball is now persistently repelled, as if by some invisible force, from the electrified rod. The pad or rubber will bring about a precisely similar effect on a fresh pith ball similarly suspended, providing care is taken not to handle the pad too much, and other precautions are taken. If, however, the silk rubber be held near the pith ball which is so persistently repelled from the rubbed glass rod, attraction at once takes place. Further, if the rod be rubbed with the silk pad and the two be brought together either to the pith ball or a suitable delicate detecting instrument, with the pad wrapped round the rod as it is during the operation of rubbing, no effect will be detected on either pith ball or instruments. Or, again, if all the electricity of the rubber and thing rubbed be imparted to a third body, this body will show no signs of electrification whatever. The above, then, shows us that in the act of rubbing the glass rod apparently two kinds of electrification have been produced, one on the rubber and the other on the thing rubbed, and further, that these have exactly opposite effects, apparently neutralising one another when brought together. Neither kind of electrification is ever produced alone, and careful experiment has shown that equal quantities of the two kinds are always produced simultaneously, one on each of the two bodies rubbed together. It is customary to call the two kinds so produced *positive* and *negative electricity* respectively, and the glass rod is charged with the former or $+^{ve}$, the rubber or silk pad with the latter or $-^{ve}$ electricity.

All substances are capable of being electrified to some degree, some much more than others; and though electricity is produced when any two substances of a different nature are rubbed together, it is *not always* apparent, for reasons which will be given presently (p. 24). The degree or intensity of electrification of any body is termed its **charge**, and this is proportional to the *quantity* of electricity on that body.

Mutual Action of Electrified Bodies.—Suppose that two similar pith balls are each hung by means of a dry silk thread from the arm of some suitable support, so as to hang quite close to one another. If now an electrified body be made to touch both balls, these will be repelled from one another and from the body which touched them, and this repulsion will continue after the body has been removed from the vicinity. The pith balls are manifestly charged with the *same* kind of electricity, and therefore we see that—*Like kinds of electricity repel one another.*

If, however, two pith balls, similarly suspended from two separate stands, be electrified, the one by the rubber and the other by the body

rubbed, they will be attracted towards one another when brought near each other. The balls are now evidently charged with opposite kinds of electricity (p. 20), and therefore we see that—*Unlike kinds of electricity attract one another.* Further, if a non-electrified body is brought near one that is electrified, attraction ensues, thus indicating that the action is *mutual.*

Conduction and Insulation.—Suppose an electrified body to be suspended from the end of a long and dry silk thread held in the hand. It will be noticed that immediately after the source of electrification is removed the body attracts light articles rather strongly, but that this attraction becomes more feeble as time goes on, until in a short time it appears not to be electrified at all. If the silk thread be damp the apparent loss of the charge is much more rapid, while if a metal wire is used as the suspension the loss or *discharge,* as it is then commonly termed, is instantaneous. In fact, in this latter case it is apparently impossible to electrify the body. This loss of electrification is explained by saying that the dry silk offers the greatest obstruction or *resistance,* as it is termed, to the passage of the electricity with which the body is charged, while damp silk offers less, and the metallic suspension least resistance of all.

Substances that behave in the same kind of manner as the dry silk above mentioned, in not offering much facility for the passage of electricity through them, are usually termed *non-conductors* or *insulators* (*i.e.* isolators), while substances which behave like the metallic suspension are termed *conductors.*

There are, however, substances which come under a third category, having insulating and conducting properties intermediate between the above-named, and these we may term *partial insulators* or *conductors.* It must, however, be remembered that these terms are only 'comparative' in their meaning, for *all substances conduct electricity to some extent,* and even the best conductor has *some* resistance.

It is very difficult to give a list of conductors and insulators in the order of their conducting power, owing to the effect of temperature and quality of the same kind of substance considerably altering its resistance. The following list of substances will give a rough approximation, however, of the class to which they properly belong :—

TABLE I

GOOD CONDUCTORS		Silver (annealed)		BAD INSULATORS
		Copper (,,)		
		All other Metals		
PARTIAL CONDUCTORS	Fairly good Conductors	Gas Coke	Fairly bad Insulators	PARTIAL INSULATORS
		Charcoal		
		Graphite		
		Plumbago		
		Dilute Acids		
		Metallic Salts		
		Saline Solutions		
		Metallic Ores		
		Water (impure)		
		The Body		
		Moist Earth		
		Flame		
	Poor Conductors	Cotton	Poor Insulators	
		Dry Woods		
		Stone		
		Marble		
		Dry Paper		
BAD CONDUCTORS		Oils		GOOD INSULATORS
		Shellac		
		Paraffin Wax		
		India-Rubber		
		Porcelain		
		Silk		
		Ebonite		
		Slate		
		Gutta-Percha		
		Sulphur		
		Resin		
		Sealing-Wax		
		Mica		
		Pure Water		
		Glass		
		Wool		
		Dry Air		

In the foregoing table those substances bracketed together are not in order of conducting power or, as it is termed, *conductivity*; but *silver* (annealed) is the very best conductor and worst insulator known, whilst *dry air* is the very best insulator or worst conductor of any.

All insulating substances insulate best when quite dry, but an increase of temperature in the majority of cases diminishes their insulating properties. We shall, however, have occasion to return to the question of conductivity and resistance more in detail in a later chapter, when dealing with another portion of this subject.

The foregoing table and remarks enable us to understand why,

when any two different substances are rubbed together, the electrification invariably produced is not always apparent. Whether it is, or is not, depends on whether one or both substances are conductors or insulators. If one is an insulator and the other a conductor, then the former will be electrified and the latter not. If both are conductors, then neither will show signs of electrification; while if both are insulators, each will show electrification. Obviously the charge imparted to a conductor flows away as fast as it is supplied, but if the conductor is supported on an insulating substance it will show signs of electrification all over, even though it be rubbed at one part only.

Electrification and its Origin.—By employing suitable precautions it can be shown that if two insulated conductors be put simply in contact, each becomes fully though feebly electrified, though no rubbing has taken place, and no increase in electrification would be produced if they were rubbed. This, coupled with the fact that any two substances of the *same nature* show *no* signs of electrification when rubbed together, indicates that the actual origin of the electrification considered in the preceding pages lies in the *contact of dissimilar substances* and *not in the rubbing.*

When, however, one or both of the substances are bad conductors, it is absolutely necessary to rub them together in order to bring the various parts of the surfaces of the two bodies successively into intimate contact, which is the sole object of the rubbing.

Moreover, the electrical energy stored up in the rubber or thing rubbed after they are separated is the equivalent of the work done in separating them against the attraction which the two kinds of electrification thus produced have for each other. Thus the degree of electrification obtained does not in any way depend on the rubbing in itself, but solely on the nature of the two substances and the efficacy of their contact.

Electric Density.—The distribution of a charge of electricity on any body depends on the shape of the latter and on its proximity to other bodies. The quantity of electricity on a unit of area (square inch or square centimetre) at any part of a charged body is termed the *Electric Density* at this part, and which is proportional to that quantity.

In the case of a charged sphere the density is uniform all over, but with irregular bodies it is greatest at the smallest part. The density is *nought* on the inner surface of a closed conductor; in other words, an electric charge resides solely on the outside surface of a body, and therefore, so far as electro-static charges are concerned, it is immaterial whether the conductor is solid or hollow metal, or whether of any other substance coated with any kind of metallic foil. If Q be

the quantity of electricity on a small surface having an area S, then the *Surface* Density $\rho = Q/S$.

Laws of Electro-static Attraction and Repulsion.—There are two important fundamental laws of electric force relating to the attraction and repulsion of electrically charged bodies, namely :—

1. *Like kinds of electricity repel one another.*
Unlike kinds of electricity attract one another.

2. *The force of electro-static attraction or repulsion exerted between two electrically charged bodies is proportional to the product of the quantities of electricity with which they are charged, and inversely proportional to the square of the distance between them.*

The first of these laws has already been considered sufficiently (p. 21), but the second will now be considered a little more in detail.

The law is true only when the charges are concentrated at points, but is approximately true when the size of the bodies is small compared with the distance between them.

Let Q_1, Q_2 represent the quantities of electricity with which two small spheres are charged, and d = the distance between their centres.

Then the force F of attraction or repulsion, depending on whether they are charged with unlike or like kinds of electricity, will be

$$F \propto \frac{Q_1 Q_2}{d^2};$$

but it is obvious that the force will depend upon the facility which the intervening medium offers for it to act through.

Hence if σ be the 'specific inductive capacity' (p. 29) of the intervening and surrounding medium, and which is a specific constant representing the ratio of the value of F in air to its value under the same conditions in the given medium, then

$$F = \frac{1}{\sigma} \cdot \frac{Q_1 Q_2}{d^2}.$$

Now air is the standard of reference or for comparison in the same way that sea-level is the standard level with which to compare heights and depths; further, the value of σ for air is so very nearly 1 that in practice it is always taken as 1. Hence if $d = 1$ centimetre and $F = 1$ dyne (p. 60), we obtain the definition of a unit quantity of electricity, by means of which standard we are able to measure or compare other quantities. Thus :—

One unit of electricity is that quantity which, when placed at a distance of one centimetre in air from a similar and equal quantity, repels it with a force of one dyne.

It will be seen from the above relation that if F is + ^{ve}, the force is one of repulsion; but if − ^{ve}, then the force is one of attraction.

The unit just defined is termed the C.G.S. unit of quantity in electro-statics, and is in terms of a system of absolute units known as the centimetre-gramme-second (C.G.S.) system, to be dealt with in a later chapter.

Some examples will illustrate the application of the above law:—

Example 1.—What will be the force exerted between two quantities of electricity of magnitudes = 4 and 16 units respectively, when placed 2 cms. apart? Assuming that σ in the formula is unity, we have—

$$F=\frac{1}{\sigma}\cdot\frac{Q_1Q_2}{d^2}=\frac{1}{1}\cdot\frac{4\times16}{(2)^2}=\frac{64}{4}=16 \text{ dynes.}$$

Note, if both quantities are of the same sign, the force is one of repulsion, indicated by the result being a positive quantity. If one is − ^{ve} and the other + ^{ve}, then the force will come out − ^{ve} and will be one of attraction.

Example 2.—What quantity, which when placed 4 cms. away from a similar and equal quantity, will repel it with a force of 4 dynes?

Here we have $F=\frac{1}{\sigma}\cdot\frac{QQ}{d^2}=\frac{Q^2}{d^2}$, for the two charges are equal, and $\sigma=1$.

Hence $$Q^2=Fd^2=4\,.\,16=64,$$

or $$Q=8 \text{ units.}$$

So that each charge must consist of 8 units of similar sign.

Example 3.—If two quantities of 6 and 8 units of electricity respectively repel one another with a force of 12 dynes, what is the distance between them?

Here $$F=\frac{1}{\sigma}\cdot\frac{Q_1Q_2}{d^2} \quad \text{and } \sigma=1,$$

$$\therefore \quad d^2=\frac{Q_1Q_2}{F}=\frac{6\times8}{12}=4,$$

or $$d=\sqrt{4}=2 \text{ cms.}$$

Electric Potential: Difference of Potential.—Most of us have noticed at some time or another the arrangement commonly adopted for the purpose of driving into the ground the piles employed for wharfs and piers, namely, that of an engine raising a heavy weight to a certain height above, and directly over, the top of the pile to be driven. The weight is then allowed to fall quickly, under the action of gravity, on to the end of the pile, the impact driving it a certain distance into the ground.

Now when the engine has raised the weight to the top, this

weight will possess a certain amount of *latent* or *potential energy* by reason of its position or the level to which it has been raised. The gain of potential energy by the weight is equivalent to the work done by the engine on the weight, against the force of gravity. But the weight is now able to do work at any instant, and the amount it would do in driving the pile, if allowed to fall, is equal to that expended by the engine in raising it. If it were raised to a higher level more work would be done, but its potential energy would be greater in proportion. Thus we see that level corresponds to potential and to capacity for doing work, and that some work must be done before weight has any potential. Strictly analogous with the above is the theory of electric potential, as it is termed; for if a body is charged with electricity, it is said to have a certain potential, by reason of its charge, relatively, of course, to surrounding objects, just as the above weight has potential by reason of its level. Moreover, the charged body is capable of doing work; for, if connected by a conducting path to some other object, a quantity of its charge will flow away from it along the path, and in so doing will perform work.

Hence the electric potential of a body is its degree of electrification, and is its capacity for doing work; and, further, one that is charged to twice the potential can do twice the amount of work, in the same way that the weight, if raised to twice the height, is capable of doing twice the work. Now, in the case of the weight, the work done is proportional to the *difference in level* of the two positions of rest of the weight; one of these being the top of the pile, and the other, perforce, that to which the weight is raised.

So it is with electricity, the *difference of potential* being proportional to the work it is possible to do.

Potential of the Earth taken as Zero.—Potential, like many other things, has to be measured relatively to some datum line or zero, in the same way that heights and depths at any place are measured from sea-level, or that temperatures are measured by taking the temperature of some definite body as zero. In neither of these instances do we infer that no lower temperature than that of melting ice (which is taken as the zero), or that no lower level than the surface of the sea, can be obtained. On the contrary, we know quite well that much lower points in both cases can easily be obtained. Such zeros are therefore quite arbitrary; and so it is with the measurement of electric potential, for we take the *potential* of the *earth* as the datum line and call that *zero*, but it is quite an arbitrary one, and, so far as being an absolute zero goes, experiment shows beyond doubt that the earth is always more or less charged, and therefore possesses

a certain potential which is by no means the lowest potential that can be produced.

The potential of a body is therefore the difference of its potential from that of the earth, and a quantity of electricity is always assumed to flow from a body at higher potential to one at lower potential when the two are connected by a conducting path; and if no flow takes place under these conditions, the bodies are said to be at the same potential, which may be zero, very high, or any intermediate one. When a body charged with $+^{ve}$ electricity is connected with the earth, the charge flows out of the body to earth; but if the charge were $-^{ve}$, then electricity passes from the earth to the body. Such a flow, however, in whichever direction it takes place, in no way affects the charge or potential of the earth, each of which is so enormous as to make any other charge or potential entirely insignificant.

Electrical Induction.—Suppose a positively charged body D (Fig. 9), such as, for instance, a glass globe, which is supported on an insulating stem S, provided with a foot F, and which has been rubbed with a silk pad, be brought near one end B of a cylindrically shaped *uncharged conductor* AB which is in two halves at the line C, each being supported by an insulating stand S with a foot F. Then some curious phenomena result, which we shall consider somewhat in detail; the principle involved, together with the action that occurs, being one of extreme importance, and underlying the action of some well-known electrical engineering appliances. In the first place, although the conductor AB, to begin with, was entirely unelectrified, and has neither been touched by the $+^{ve}$ charged body D nor rubbed, it will now be found to be electrified at each end, though not in the middle.

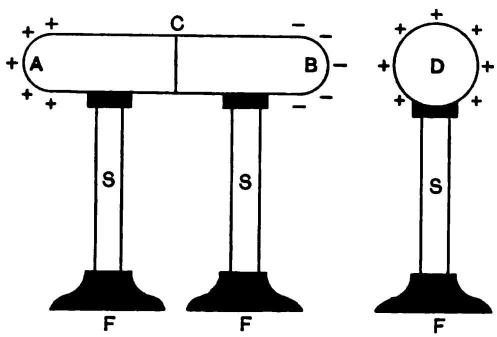


FIG. 9.—Electro-static Induction between a Globe and Cylinder.

The end B nearest D is found to be negatively charged, while the other end A is charged with positive electricity; and further, that these two opposite charges are exactly equal in amount. It is evident therefore that the $+^{ve}$ charge on D has the power of *inducing* a $-^{ve}$ charge at B, which it attracts, and a $+^{ve}$ one at A, which it repels;

and that this action, which is called *Electric Induction*, can go on at a distance, when the two bodies are separated by air or any other insulating substance.

If D be removed to a distance from AB, it will show no loss of charge, while AB will show no further signs of electrification at either end, the two equal induced charges having apparently neutralised one another.

Again, if while D is near to B, as first considered, the two halves A and B be separated, then A will be found to be positively charged and B negatively, and each will remain so even though D be removed right away, for now the charges cannot combine to neutralise one another.

Lastly, if with the conditions represented in Fig. 9 the end A, or indeed any part of AB, be touched with the finger for an instant, the $+^{ve}$ charge at this end will flow away to earth, and only the end B will now appear to be electrified with the opposite kind of electricity to that with which D is charged. The $-^{ve}$ charge at the end B is spoken of as being *bound*, because it is attracted by the presence of the neighbouring $+^{ve}$ charge on D, and cannot flow away so long as D is near it. The $+^{ve}$ charge at A is spoken of as being *free*, because it can flow away instantly on a conducting path being provided *from any point* of the conductor AB.

The amount of electricity at each end of AB will depend upon that on D, the intervening medium, and upon the distance between B and D, and will increase as the charge of D is increased, and as the distance diminishes. Evidently, then, for a given charged body such as D, the limit in the magnitude of the charge at A or B will be when D is almost touching B, and then the induced charge will be almost equal to the inducing charge.

Specific Inductive Capacity.—In the preceding instance of electric induction, the action took place across an intervening stratum of insulating medium, namely, *air*; but, as was previously mentioned, it could take place when any other insulating medium is employed. It has, however, been conclusively shown that the nature of this medium plays a most important part in the action and in the facility thus offered for the inductive electric influence to act through it.

The facility or power possessed by any substance for allowing the inductive action to take place across it is termed its *inductive capacity*, and the substance itself is termed a *dielectric*.

Air and all other gaseous dielectrics have a small inductive capacity, and if any other solid insulating substance had been placed between D and B (Fig. 9) the charge induced at A or B would have been greater for that same distance.

All dielectrics are necessarily insulators, though any insulator may not be a good dielectric.

A good dielectric has a high inductive capacity—for instance, dense flint glass, which is nearly one of the best in this respect. Gaseous dielectrics are the worst.

Now it is evident that the inductive capacity of any medium is a specific constant for that medium, depending in magnitude, as we have seen, upon that property of the medium which determines the facility with which electric force acts through it. This constant is determined with reference to some convenient standard substance whose inductive capacity shall be taken as unity. The substance chosen is dry air at a temperature of 0° C. and 760 mm. pressure of mercury.

Hence the constant expressing the ratio of the magnitude of the charge induced at B (Fig. 9), when separated from D by a given dielectric, to that induced when air at 0° C. and 760 mm. pressure is substituted, everything else being the same, is called the *specific inductive capacity* of the given material or dielectric.

The following table (II.) gives the approximate values of the specific inductive capacity of some important substances commonly met with in electric engineering work :—

TABLE II

Substance or Dielectric.	*Specific Inductive Capacity.*
Dry air at 0° C. and 760 mm.	1·00 taken as standard
Paper (known as butterskin)	1·86
,, (saturated in resin oil)	2·4
,, (diatrine)	...
Pitch	1·85
Beeswax	1·86
Paraffin wax	1·92 to 2·32
,, oil (sp. gr. 0·28)	1·98 to 2·32
India-rubber or caoutchouc (pure)	2·0 to 2·8
,, ,, ,, (vulcanised)	2·8 to 3·1
Resin (solid)	1·78 to 3·0
,, oil	...
Ebonite	1·9 to 3·15
Shellac	2·95 to 3·70
Sulphur	2·24 to 3·8
Gutta-percha	3·30 to 4·9
Mica	4·6 to 8·0
Glass (ordinary)[1]	About 3·0
,, (light flint)[1]	6·5 to 6·9
,, (dense ,,)[1]	7·4 to 10·0

[1] The values given depend on the density of the glass and on the duration of the charge during test, the specific inductive capacity being increased with increase of density and decreased with a shorter duration of charge. This, for the value given, is between 0·250 and 0·00005 of a second.

TABLE II.—*continued*

Substance or Dielectric.	*Specific Inductive Capacity.*
Porcelain	About 43·8
Ozokerite	,, 2·15
Petroleum oil	2·02 to 2·19
Celluvert (hard grey)	About 1·18
,, (,, red)	,, 1·45
,, (,, black)	,, 1·90
,, (soft red)	,, 2·67
Micanite	...
Okonite	About from 3 to 5
Benzine	2·198
Benzol	2·38
Colza oil	3·07 to 3·14
Water (150°)	2·23
Glycerine	About 5·6
Hooper's compound	3·1
White castor oil	4·92
Olive oil	3·0 to 3·5
Ordinary kerosene	2·22
Neatsfoot oil	3·2
Tar	1·8
Turpentine (common)	2·23

It may be noted in passing that at the present day the question of specific inductive capacity of insulating materials is becoming of considerable importance in connection with what are termed electrical cables. The reason for this we shall, however, defer stating until a subsequent chapter, when the explanations and terms connected therewith will be better understood at that stage than now.

Induction precedes Attraction.—The foregoing remarks on inductive capacity will enable us to see how it is that an electrified body is able to attract one that is not electrified. Thus the former first induces a charge of *opposite sign* to its own on the nearest portion of the non-electrified body, and a charge of the same sign on the portions farthest away. Now the charges of like sign repel, but those of unlike sign attract, and since these are closer than the former, attraction ensues.

If, however, the two bodies touch for an instant, the whole of one of the unlike charges of one body just neutralises an equal charge of the opposite sign on the other body, thereby leaving both bodies charged with the same kind of electricity, and therefore repulsion now ensues persistently (*vide* p. 21).

From what has already been said, the reader should be in a position not to confuse the terms *conduction* and *induction*; for the former clearly implies a *transfer* of electricity, while induction merely refers to a *redistribution* of electricity without any transference to or from the body.

Space will not permit of a description of the machines and appliances for producing statical electricity, nor of many other phenomena connected with this subject.

The principles enunciated, however, in this chapter are those which mostly concern the electrical engineer, and many of them, it will be seen, are required in order to understand the action of many practical and widely used appliances, as well as the phenomena of capacity and theory of condensers, which will be dealt with in a future chapter of this book.

QUESTIONS ON CHAPTER II

[*Supplement all Answers with Sketches when possible.*]

1. Distinguish between *conduction* and *induction* with regard to electrified bodies.
2. Give the laws for the mutual action of electrified bodies on one another.
3. Define the terms inductive capacity, specific inductive capacity, electric density.
4. Two bodies are charged respectively with 5 and 200 units of electricity. What will be the distance between them when the force exerted = 10 dynes?
5. Distinguish between conductors and insulators of electricity, and arrange the following substances in order of conductivity—carbon, zinc, glass, and paper.
6. Find the force with which two charges of 2 and 100 units respectively of opposite signs would act when placed 8 cms. apart in air.
7. Carefully describe what is meant by *electric potential* and *potential difference*.
8. What is the magnitude of the charge which, when placed 4 cms. away from one of 32 units, repels it with a force of 6 dynes?
9. Find the density on the surface of a spherical conductor, free from all outside influence, when its radius = 10 cms. and charge = 1000 units.
10. Explain the real cause of electro-static attraction and repulsion.

ELECTRICITY (CURRENT)

CHAPTER III

FUNDAMENTAL PRINCIPLES

Introduction to Current Electricity.—In the two preceding chapters on magnetism and statical electricity many important principles and laws have been given, the connection of which with the study of electrical engineering may not strike the reader at this stage. Such principles as those already mentioned, together with many others of like nature, though belonging to the pure science of physics, nevertheless form the basis on which the scientific world began to build the electrical engineering industry during the latter half of the past century.

It was not until the possibilities of that subtle agent which we term 'electricity' came to be realised as a means of lighting and transmission of power that an impetus was given to scientific research, resulting, as we see at the present time, in electricity being employed for many purposes that earlier lighting means, such as candles, gas, and oil, or power agents, such as water, horses, steam, had been used for.

The Electric Current—Its Nature and Direction of Flow.—In the foregoing pages we have only had occasion to speak of 'electricity' at rest, as in the form of a *charge* on a body, though mention has been made of the momentary *flow* of electricity when such a body was discharged. In the following pages, however, we shall have occasion to speak almost entirely of a 'current of electricity' flowing 'along or through' a conductor. In one way this expression is an unfortunate one, although it is one of universal adoption, because the words *current* and *flow* might naturally lead us to imagine that a stream of some material substance was actually passing along the conductor. Nothing of the sort can of course be seen, and the outward appearance of the conductor remains entirely unchanged, whether a so-called 'current of electricity' is flowing in it or not. The expression, in

other words, is purely a *conventional* one, employed for convenience to denote that the conductor and space surrounding it possesses certain characteristic properties which it does not usually have. Some authorities take up a more modern view regarding the flow of a current in a conductor, namely, that the ether surrounding the conductor, and not only the conductor itself, is the medium through which the transfer takes place. According to this theory the transfer of energy is supposed to take place in the form of electro-magnetic waves along the path followed by the conductor. The idea, however, is purely hypothetical.

Totally ignorant, as we are, of the nature of electricity, and of whether there is anything in motion or not in a conductor said to be carrying a *current*, we are equally at a loss to know in which direction such a flow, if it actually exists, takes place. All we know in connection with the direction of flow is that the properties and effects exhibited have a definite sense or direction of action when the current is said to be flowing in one direction along a conductor, and an exactly opposite sense or direction when the current is said to be flowing in the other direction.

Thus the *direction of flow* is also entirely *conventional*, and when we say that the flow takes place from a point of high potential to one of low potential, which is universally taken to be the case, we are making a pure assumption.

At the same time the reader must not go away with the idea that the assumptions of electricity being capable of flowing in the form of a *current* and also of flowing in a certain direction are unjustifiable. Imagine the lower half of a very light paddle-wheel to be inserted in a hole cut in the side of a pipe, and free to rotate. On blowing air through the pipe in one direction the wheel will turn, whereas by blowing in the opposite direction the wheel would turn in the reverse sense to what it did before.

Here evidently we have a very analogous case to electricity—the current of air which cannot be seen, and which does not in any way alter the appearance of the pipe, naturally flows from the end at highest pressure, producing an effect (*i.e.* rotation of the wheel) in a certain sense or direction. If the current of air is reversed in direction, it is equally invisible, but produces opposite effects (*i.e.* rotation of the wheel in the opposite direction). Moreover, the current of air, like one of electricity, would have no existence apart from its conducting path; but the analogy, like many others, must not be pressed too far, for in the case of the air we know that matter in motion is being dealt with, although invisible.

Consequently the terms '*current*' and '*direction of flow*,' when applied to electricity, are purely conventional terms, which quite naturally suggest themselves to us for convenience in speaking about the subject. Now in the various branches of the electrical engineering industry, as for instance telegraphy, telephony, electric lighting, electric traction, electro-plating, -typing, and -refining of metals, etc., it is this electric current which is employed. Hence to understand the working of the many electrical appliances and phenomena met with in these branches, and, further, to be able to advance any one or more of these branches by new improvements and inventions, it is absolutely necessary to acquire a sound knowledge of the scientific basis of the profession —in other words, a sound knowledge of the laws, properties, and methods of measurement of the so-called electric current.

Properties or Effects produced by an Electric Current.—It has already been mentioned that a current of electricity has no existence apart from the conductor in which it is said to be flowing, and, furthermore, that nothing can be seen of it. We may therefore preferably say that a conductor carrying a current exhibits such and such properties, or produces certain characteristic effects. It is consequently by these only that we are able to measure and deal with it. The effects in question are five in number, as follows :—

The Magnetic Effect, which is invariably produced when a current flows in any circuit whatsoever. In virtue of this a magnetic field (*vide* p. 6), consisting of lines of magnetic force, is created around the circuit, and acts magnetically on any body in the vicinity. This property of a conductor conveying a current in thus apparently becoming what is termed an electro-magnet is made use of in a great number of different appliances employed in the electrical engineering industry, such as dynamos, motors, transformers, electric bells, telephones, etc.—in fact, in all appliances containing an electro-magnet.

The Heating Effect, which is always present whenever a current, however small, flows in a circuit. This property is made use of in electric lighting by both arc and glow lamps, electric heating and cooking, and for many other purposes.

The Chemical Effect, which is produced whenever a unidirectional current flows through a circuit composed partly or wholly of a liquid. This liquid is decomposed into its constituent parts, which appear one at either point where the current enters and leaves the liquid.

This property of an electric current is made use of in primary and secondary cells, electro-plating, electro-typing, and refining of metals, etc.

The Physiological Effect, which is produced when an electric current flows through any part of the human or animal frame. The

result may be either a temporary or permanent paralysis of the nerves and muscles, depending on the strength of the current passing. This property is made use of in several branches of medical science for curing different ailments, and is becoming more and more popular every year for such purposes.

The Physical Effects.—These comprise such phenomena as electric osmose, distillation, and electro-capillary action, about which comparatively little is known.

Application of the Effects.—It will now be seen that the only possible way of utilising the agent which we are pleased to call 'electricity' is by means of the effects which it produces, and it is on these alone that the very existence of the electrical engineering industry depends. It will, moreover, be equally obvious that we are entirely dependent on these effects for the ways and means of all measurements connected with electricity, and of other conditions or qualities pertaining to electrical circuits.

Before considering more in detail the practical applications of the foregoing effects to the heavier appliances, it will be necessary to see how they can be applied in the case of systems of measurement.

We here come to a real source of difficulty, and one that has been keenly felt in the past, namely, which of the five effects mentioned above can best be employed for measuring a current. A little reflection will make it clear that, whichever effect is chosen, it ought to be one that is *directly* proportional to the current producing it, irrespective of the size, shape, and make of the particular appliance chosen to exhibit the effect.

To commence with, only the *magnetic*, *heating*, and *chemical* effects have to be considered at all.

In the case of the magnetic effect experiment shows that this effect is not directly proportional to the current in every instance, and, further, that the size, shape, and make of precisely the same type of measuring appliances cause any two to indicate to a different degree.

In the case of the heating effect the difficulty is similar, but to even a worse extent, and is further augmented by the fact that the amount of heat produced by a current can only be measured indirectly by rise of temperature, to which it is not directly proportional owing to loss of heat by radiation, convection, and conduction.

With the chemical effect, however, the case is different, and we will therefore consider it more in detail. It has already been stated that when a unidirectional current passes through a liquid, this latter is split up into its constituent parts. This, however, does not happen in the case of all liquid substances, for some scarcely conduct at all,

while others conduct but are not acted on by the passage of the current through them. Liquid substances such as water, solutions of metallic salts, dilute acids, etc., which are decomposed by the passage of a current through them, are termed *electrolysable* substances or *electrolytes*, and the action thus taking place *electrolysis*.

The vessel in which this action goes on is called an electrolytic cell, or very often a voltameter, and the ends of the metallic circuit, usually in the form of plates, whether flat or cylindrical, are termed the electrodes of the cell.

Further, the electrode at which the current enters is called the *anode*, and that by which it leaves is called the *cathode*.

Now the above terms are applied to all kinds of voltameters, as, for instance,—*copper voltameters*, consisting of two copper plates or electrodes dipping into an electrolyte or solution of copper sulphate; or *silver voltameters*, consisting of two silver electrodes separated by a solution of silver nitrate; or *mixed gas voltameters*, consisting usually of platinum plates dipping into acidulated water, etc.

Electro-Chemical Action in Voltameters.—The voltameter as an electrical appliance, together with the action that takes place in it, is so important, that we must consider one or two of the most important kinds. These are the *copper* and *silver* forms.

In the copper voltameter, comprising two copper electrodes immersed in a solution of copper sulphate, otherwise known as *blue vitriol* and having the chemical symbol $CuSO_4$, the copper (Cu) of the anode dissolves in the solution at precisely the same rate as that in the solution is deposited on the cathode on passing a current through it. If, however, the electrodes are made of platinum (which cannot dissolve) instead of copper, the current deposits the copper (Cu) of the solution in the form of a film on the surface of the cathode, liberates oxygen gas (O) from the anode, and forms sulphuric acid (H_2SO_4) in the solution. In chemical language, the changes which occur are as follows:—

$$CuSO_4 + H_2O = Cu + H_2SO_4 + O$$

—*copper sulphate* and *water* become *copper* and *sulphuric acid* and *oxygen*. Thus the solution loses metallic copper and acquires sulphuric acid. Now if several voltameters of the *same type* (*e.g.* copper) but of different sizes, the respective plates being at different distances apart and of a variety of sizes, be connected up in different parts of a circuit through which a current is sent, it will be found that precisely the same amount of copper is deposited on the cathode of each cell in the same time. If they had been silver voltameters, then the same quantity of silver would be deposited, and so on. Further, this would be exactly the

case if the voltameters were connected end on to one another instead of at different points. We therefore conclude that *both current and the amount of chemical action produced by it is the same at all parts of a circuit at any one instant.*

Moreover it can be shown that—*the amount of chemical decomposition taking place in any kind of voltameter due to any current strength is directly proportional to the strength of this current, i.e.* ten times the strength of current will produce just ten times the amount of decomposition in the same time. This is known as Faraday's Law of electrolysis. From the foregoing considerations it is evident that a current of electricity can best be specified or defined by its chemical effect, for we have seen that within wide limits the particular construction of the same type of voltameter has no effect on the amount of decomposition. This was not so with the magnetic and heating effects, since in the case of these every detail of construction must be carefully specified in order to specify the strength of a current.

Practical Unit of Current.—We are now in a position to understand the full meaning of any definition of a unit of current which may be based on the chemical effects of a current. It will be evident that a unit of this kind is a necessity for the purpose of enabling the electric current to be dealt with at all, and in addition to enable any particular strength of current to be spoken of or compared with any other. Just as in the case of a system of reservoirs supplying water to a town a practical unit must be adopted, such as the *gallon*, to enable the volume of water to be spoken of or to enable it to be said that the supply through one pipe is so many times larger than that through another.

Now it is imperative for the unit, in terms of which electric current is dealt with, to be recognised by all the electricians and scientists of the world, so that any appliance made in a particular country may be available for use in any other country, and, further, that the research by different experimenters both at home and abroad may be of universal application.

The practical unit of electric current adopted by scientists and electricians throughout the world *is that current which deposits* 0·0011180 *gramme or* 0·017253 *grain of silver per second on one of the plates of a silver voltameter containing a neutral solution, about* 15 % *by weight of which consists of crystals of pure silver nitrate dissolved in water.*

This unit is termed an *ampere*, and though universally recognised it has not been legally defined by Government in the same way that many other units, such as those of length, mass, etc., have been.

The ampere, however, is inconveniently large for some purposes;

for example, reckoning the currents employed in telegraphy, which often do not exceed 0·003 of its value; while for other purposes it is small, as with the heavy currents used in electric lighting, traction, welding, etc., which amount to thousands of amperes. Consequently it has been found convenient to nominate sub-multiples and multiples of the ampere, which are called—

A *milli-ampere*, meaning $\frac{1}{1000}$th part of an ampere.
A *kilo-ampere*, „ 1000 amperes.

Practical Unit of Electrical Quantity.—When a current of electricity flows through a conductor or circuit for a certain time, a certain quantity of electricity will have passed through it, in much the same way that when water flows through a pipe for a given time a certain quantity will have passed through the pipe; being mindful, however, that in drawing this analogy we are dealing with a material substance in motion, whereas with a current of electricity we are not sure what we are dealing with.

The unit of electric quantity is defined as *the quantity of electricity which flows in one second past any point of a circuit that is carrying one ampere*, and is called a *coulomb*.

A coulomb is therefore an ampere per second, or, as it is more briefly stated, an ampere-second. Expressing this in symbols, we have

$$Q = A \,.\, t,$$

where Q is the quantity of electricity in *coulombs*,
A is the current strength in *amperes*,
and t is the time in *seconds* during which A has been flowing.

Thus, if 20 amperes flow for 5 minutes in a circuit, the quantity of electricity which has passed is

$$Q = At = 20 \times (5 \times 60) = 6000 \text{ coulombs.}$$

Similarly,

$$1 \text{ ampere-hour} = 1 \times (60 \times 60) = 3600 \text{ coulombs.}$$

Now this relation can equally well be written in the form

$$A = Q/t,$$

and hence we see that when a quantity of electricity flows through a conductor at the rate of 1 coulomb per second, the current strength is 1 ampere.

Thus $$3600 \text{ coulombs per hour} = \frac{Q}{t} = \frac{3600}{60 \times 60} = 1 \text{ ampere,}$$

or $$5 \text{ ,, ,, second} = 5 \text{ amperes,}$$

and so on.

In practice, the flow of a current and quantity of electricity may be either *constant* or *momentary* (transient, as it is often termed). In the former case the total quantity is easily obtained as above, since the current has one definite constant value for a definite period.

In the latter case the current commences at a small value, rises quickly to its maximum value, and then dies out, all in a very short time.

If in this case we divided the short interval of time taken for the whole discharge or charge into a large number of much smaller intervals, the total quantity of electricity in the transient current thus flowing would equal the sum of all the products of these tiny intervals and the current strength at each; or, in the language of the integral calculus, we have in such a case

$$Q=\int A\,.\,dt,$$

where dt is one of these tiny intervals of time. There are instruments for effecting such measurements as these, called ballistic galvanometers, which will be considered later on.

In the case of a steady flow, especially if the current is at all large, the quantity, if reckoned in coulombs, would give inconveniently large figures to deal with. In such cases the *ampere-hour* is taken as the unit, and we have just seen that this is equivalent to 3600 coulombs.

With transient flows, where the quantity is usually small, a sub-multiple of the coulomb, namely, the micro-coulomb, is used, the relation of the two to one another being as follows:—

$$1 \text{ micro-coulomb} = \frac{1}{1000000} = 10^{-6} \text{ coulomb.}$$

Electro-Chemical Equivalent.—This is a number expressing the weight of any element, in grammes, separated or deposited in an electrolytic cell by the passage of 1 ampere for 1 second. For instance, it was pointed out on page 38 that, by extremely careful experiment, it has been found that 0·0011180 gramme of silver is deposited by one coulomb. Hence this number 0·0011180 is called the *electro-chemical equivalent* of silver.

Similarly, 0·000010380 is the electro-chemical equivalent of hydrogen, because one coulomb of electricity in passing through a water voltameter liberates or separates 0·000010380 gramme of hydrogen.

Now there is a simple connection between this value for hydrogen and that for silver or any other element which depends on what is called the 'chemical equivalent' of such elements.

It is well known that hydrogen is the lightest substance in existence, and the weight of an *atom* of hydrogen is taken as the unit in which to represent the weight of those of all other substances.

Thus the *atomic weight* of hydrogen is denoted by 1, while that of silver is 107·7, meaning that an atom of silver is 107·7 times heavier than one of hydrogen.

Further, in chemical dissociations and combinations one atom of other substances is, in some cases, worth 2, 3, and 4 atoms of hydrogen. Thus, while 1 atom of silver is capable of replacing 1 of hydrogen, 1 atom of gold replaces and is worth 3 atoms of hydrogen.

These numbers—1 in the case of silver and 3 in the case of gold—are the 'valencies' of those elements; or, in other words, the 'replacing capability' of an atom of any substance in terms of atoms of hydrogen is called its '*valency*,' whence the *chemical equivalent* (C_E) of any substance = atomic weight (w) ÷ valency (v), or in symbols—

$$C_E = \frac{w}{v}.$$

If, now, Z_H stands for the electro-chemical equivalent of hydrogen, and Z for that of any other substance,

Then $$Z = C_E Z_H = \frac{w}{v} \cdot Z_H = 0{\cdot}00001038 \cdot \frac{w}{v}.$$

As an example, find the electro-chemical equivalent of zinc.
Here the atomic weight of zinc = 64·88,
and the valency „ = 2

$$\therefore \quad Z = 0{\cdot}00001038 \times \frac{w}{v} = 0{\cdot}00001038 \times \frac{64{\cdot}88}{2} = 0{\cdot}0003367,$$

or 0·0003367 gramme of zinc is deposited by 1 coulomb. Since 1 ampere-hour is equivalent to $1 \times 60 \times 60 = 3600$ coulombs where 1 hour is equivalent to 3600 seconds, the weight of any substance deposited by 1 ampere in 1 hour = $3600 \times Z$ grammes. So that if A amperes flow through an electrolyte for t seconds, the weight of element liberated

$$\mathbf{W} = \mathbf{A} \cdot \mathbf{Z} \cdot \mathbf{t} \text{ grammes.}$$

This is a most important relation, for it forms a means of measuring a current in amperes when the weight of deposit and the time are known.

Thus $$A = \frac{W}{Z \cdot t} \text{ amperes,}$$

where W is in grammes and t in seconds.

A few examples will familiarise the student with these two relations.

Example 1.—What weight of zinc will be deposited in a zinc voltameter by a current of 10 amperes flowing for $2\frac{1}{2}$ hours?

Taking the electro-chemical equivalent of zinc to be 0·0003367, we have the weight deposited—

$$W = A \,.\, Z \,.\, t = 10 \times 0{\cdot}0003367 \times (2\tfrac{1}{2} \times 60 \times 60)$$
$$= 10 \times 0{\cdot}0003367 \times 90000 = 303{\cdot}03 \text{ grammes,}$$

or about $$\frac{303{\cdot}03}{453{\cdot}6} = 0{\cdot}66 \text{ of a lb. (avoir.).}$$

Example 2.—Find the current that would deposit 336·7 grammes of zinc on one of the plates of a zinc voltameter in 5 hours.

Here we have the current A given by the relation

$$A = \frac{W}{Z \,.\, t},$$

substituting

$$A = \frac{336{\cdot}7}{0{\cdot}0003367 \times (5 \times 60 \times 60)} = \frac{1000000}{15000} = 66{\cdot}66 \text{ amperes.}$$

Example 3.—In what time will 111·8 grammes of silver be deposited in a silver voltameter by a current of 100 amperes?

Taking the electro-chemical equivalent of silver (Table III.) as 0·0011180, we have the time taken—

$$t = \frac{W}{AZ} = \frac{111{\cdot}8}{{\cdot}001118 \times 100} = 1000 \text{ seconds,}$$

or 16·66 minutes.

The following table gives the atomic weight, valency, chemical and electro-chemical equivalents of several elements commonly met with in practice, together with the weight in grammes deposited per hour by 1 ampere, and the best current density to employ on the electrodes immersed in the electrolytic bath.

In connection with this it should be remembered that irregular and imperfect deposits are produced by either too weak or too strong a current, and in the latter case some of the deposit does not adhere to the cathode at all.

[TABLE

TABLE III

Element.	Chemical Symbol.	Chemical Valency.	Atomic Weight.	Chemical Equivalent.	Electro-Chemical Equivalent or Grammes deposited per Coulomb.	Approximate Grammes deposited in one Hour by one Ampere.	Approximate advisable Current Density in Sq. Cms. of Cathode Surface per Ampere.
Hydrogen . .	H	1	1	1	0·00001038	0·037368	
Silver . .	Ag	1	107·7	107·7	0·0011180	4·0250	500 to 200
Aluminium .	Al	3	27	9	0·00009317	0·3355	
Copper (cupric) .	Cu	2	63·18	31·59	0·0003279	1·1832	} 100 to 50
,, (cuprous)	Cu	1	63·18	63·18	0·0006558	2·3665	
Gold . . .	Au	3	197	65·66	0·0006781	2·4411	about 1000
Iron (ferric) .	Fe	3	55·88	18·627	0·0001934	0·6957	} 500
,, (ferrous) .	Fe	2	55·88	27·94	0·0002900	1·0436	
Lead . . .	Pb	2	206·4	103·2	0·001071	3·8570	
Nickel . .	Ni	2	58	29	0·0003054	1·0993	500 to 66
Zinc . .	Zn	2	64·88	32·44	0·0003367	1·2113	330 to 160
Platinum . .	Pt	4 and 2	195	48·7 and 97·5	0·0004586	1·6508	
Tin (stannic) .	Sn	4	118	29·5	0·0003054	1·0994	
,, (stannous) .	Sn	2	118	59	0·0006108	2·1988	
Oxygen . .	O	2	15·96	7·98	0·0000828	0·29808	
Chlorine . .	Cl	1	35·37	35·37	0·000367	1·3212	

It will be noticed that of all the substances mentioned in the preceding table, silver takes the lead in the rapidity with which it is separated, whilst of the remaining metals aluminium is the slowest.

On page 37 it was mentioned that exactly the same weight of element, for example zinc, is deposited in each of a series of zinc voltameters connected up in different parts of the same circuit irrespective of size and shape. If, however, the electrolytic cells were different, as, for instance, consisting of copper, zinc, silver, and platinum electrodes dipping into solutions of copper sulphate, zinc sulphate, silver nitrate, and acidulated water respectively, then, independent of whether the cells were of the same or different sizes, the weights of copper, zinc, silver, and hydrogen separated will not be equal, but will be in *chemically equivalent* quantities.

Electrical Resistance—The Practical Unit.—We have already had occasion to refer to the obstruction or '*resistance*' which certain substances offer to the passage of electricity along or through them.

This resistance varies with the nature of the substance, being extremely high for some and very little for others; but whatever the substance and its resistance may be, the current that it will carry depends on the magnitude of the pressure. In fact, the limit to the current which any conductor can carry is the point at which the conductor is fused in two, and this in turn depends on the available pressure. We have a striking analogy to this in the case of a water-pipe supplied by a cistern, in so far that the flow depends on the

magnitude of the pressure or 'head' of water as it is termed, *i.e.* on the height of the surface of the water in the cistern above the outlet of the pipe below it. The flow will be much more rapid as the pressure or *head* of water is increased, and the limit to the amount of flow will take place when the pressure becomes so great as to burst the pipe.

It will be evident, therefore, that resistance cannot be measured by considerations of current strength alone, and we shall see presently that the pressure must be taken into account as well.

For the present, however, we must be content with considering the unit in terms of which resistances are measured or compared; for, like almost everything else, some convenient unit must be adopted. It is, moreover, essential that it should be of such a nature as to be easily and accurately reproduced. In the past there have been several units of resistance in this country and on the Continent, which fact has led to a good deal of confusion, since electrical apparatus made in one country is often used in another. For the first time, in 1863, a unit of resistance was evaluated and defined, after a vast amount of research, by a Committee of the British Association in London, in terms of a *velocity* as obtained with a coil of known dimensions rotating in a known magnetic field at known speed. This was called a '*B.A.*' *unit of resistance* and its value given as 1,000,000,000 cms. per second.

Some fifteen years later doubts arose as to whether this determination was correct, and it was realised that such a standard was inconvenient for reproduction. Further, that instead of employing lengths of German silver wire as practical standards, carefully standardised by comparison with this rotating coil, the idea originally suggested by *Siemens* should be adopted, namely, that of defining the unit as the resistance of a certain length of pure mercury of given cross section at a certain temperature.

It was therefore decided in 1881 that the whole determination should be repeated, which was done extremely carefully, and in 1884 the International Electrical Congress at Paris decided that the standard legal unit of resistance should be that of a column of pure mercury which should have the same resistance as the carefully redetermined value of the B.A. unit. This column they decided should be 106 cms. long, 1 sq. mm. in area at 0° C.; the decimal of a cm. which should be added to the 106 to make the length accurate being omitted pending further research. This unit is called the *Paris legal ohm.* Finally, it was decided (in 1892), after extremely careful and painstaking research with more carefully constructed and elaborate apparatus and

methods, of which that due to *Lorenz*[1] stands in the first rank, that *the legal unit of resistance is that offered to a direct current between the extreme ends of a column of pure mercury* 106·3 *centimetres long*, 1 *square millimetre in cross sectional area throughout, weighing* 14·4521 *grammes, at a temperature of melting ice, or* 0° C. This is the legal unit of resistance, of international adoption at the present day, and is variously termed an '*ohm*,' '*legal ohm*,' '*standard ohm*,' or '*Board of Trade true ohm*' (often abbreviated to B.O.T. ohm). It may be mentioned that the *mean* of the results obtained for the length of column, 1 sq. mm. in section at 0° C., by several eminent experimenters is actually 106·243 cms.; but the value stated previously, namely, 106·3, is defined by 'Order in Council,' and has been agreed to by the Governments of Great Britain, France, Germany, and the United States.

Moreover, there is every reason to suppose that it is an extremely close approximation to a velocity of 10^9 or 1,000,000,000 cms. per second, and it is highly improbable that any other value will be assigned to it. The small Greek letter ω is often used as an abbreviation or symbol for the word *ohm*. Thus 100 ω means 100 ohms. Since even at the present day we are constantly coming across and using earlier resistances which were naturally standardised in terms of the B.A. unit, while all those made now are in terms of the B.O.T. true ohm, it is important to note the relation, in order that one can easily be converted into the other. This is as follows:—

1 B.A. unit or ohm = 0·9866 B.O.T. or true ohm (the international unit).
1 B.O.T. or true ohm = 1·01358 B.A. unit or ohm.
1 Paris legal ohm = 1·01071 B.A. ohm.

In some cases the ohm is found to be an inconveniently small unit of resistance, in others far too large. To meet this objection the prefixes micro- and meg- are often used with it to denote a millionth part and a million.

[1] This method consists in causing a metal disc about 12″ in diameter and $\frac{3}{16}$″ thick, instead of a closed coil, to rotate at a uniform speed in a magnetic field produced by a coil of insulated wire surrounding it and concentric with it. This coil of 100 or 200 turns may have an axial width of some 6″, with an internal diameter a little greater than the external diameter of the disc. It is connected in series with a fairly constant battery and any convenient resistance to be measured. Thus the disc cuts the field due to the coil, and the speed is adjusted so that the E.M.F. induced in the disc between centre and periphery just balances the fall of potential between the extremities of the resistance, as indicated by a delicate galvanometer connected up in the potential wires connecting disc and resistance. Then it can easily be shown that the Resistance is = a constant × speed in revolutions per second, or = a length in centimetres ÷ a time, *i.e.* a velocity in centimetres per second. The constant is the so-called coefficient of mutual induction between coil and disc, which is calculated from the dimensions of the apparatus with the utmost care. (*Phil. Mag.* Jan. 1889, and *Proc. Phys. Soc.* Nov. 1888.)

Thus $\quad$ 1 microhm $= \frac{1}{1000000}$th of an ohm.
1 megohm $= 1,000,000$ ohms.

The former is used in conjunction with good conductors, the latter in the case of insulating substances.

Electrical Conductance—Practical Unit.—The electrical conductance of a conductor or circuit is the quality in virtue of which it affords facilities to the passage of an electric current.

Obviously, then, conductance is exactly the opposite, or the reciprocal of resistance, and it is measured in terms of a unit called the '*MHO.*'

Thus $\quad$ 1 mho = 1 ohm,
and $\quad$ 10 mhos $= \frac{1}{10}$ ohm,
or $\quad$ 0·1 mho = 10 ohms.

This unit of conductance, however, is not very often used.

Electrical Pressure.—In chapter ii. p. 26 we have indicated what is meant by electric potential and also potential difference, drawing an analogy to aid the explanation. We may now somewhat amplify those remarks, and apply them more particularly to the case of current circuits.

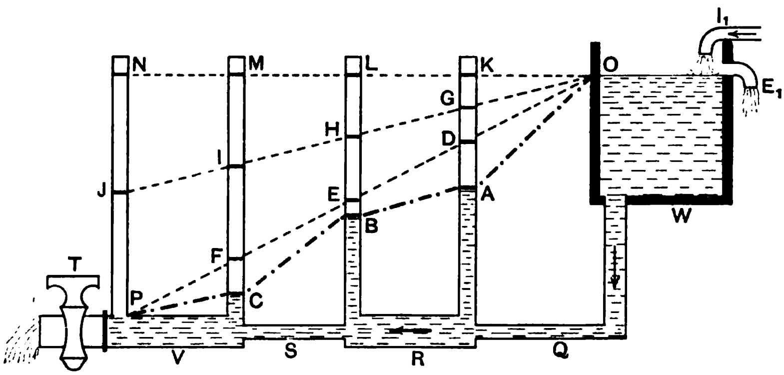


Fig. 10.—Water-Pressure Analogue.

It was pointed out on page 38 that the current flowing in any circuit has the same strength at all points at the same instant. This, however, is not the case with the potential, which varies from any one point to the next, and is not the same at any two points of a circuit at the same instant.

The analogy to a water-pipe is helpful in understanding what occurs, and a reference to Fig. 10 will make it clearer still. Let W be a water-tank, from the bottom of which is led a pipe connecting with a horizontal pipe which is composed of four lengths Q, R, S, V of varying cross section or bore. At the junctions of the pipes of

different bores a glass stand-tube, open at its upper end, is fitted, as at K, L, M, N; and by means of a tap T the end of QRSV can be opened or closed to regulate the flow of any liquid. An exit or waste-pipe E is fixed to the tank W so that the supply of water through the inlet-pipe I_1 maintains a *constant level* of water in W up to O. Some extremely interesting and instructive effects can now be obtained, which are strikingly analogous to some met with in an electric circuit, and these we will consider in some little detail.

In accordance with a well-known principle in hydrostatics, when T is shut the water will rise in each stand-tube until the top of each column lies in one and the same horizontal straight line ON with the surface of water in the tank. But since each tube is open at the top, the height of any column at any time and under any condition of flow will represent the pressure of water in the main QV at the particular point where that stand-tube joins it Hence with T shut the pressure at all points in QV is *uniform*, and so long as the level of water in W is kept at O this pressure will also be *constant*. Its magnitude is represented by the vertical height NP called the '*head*' of water, so that the difference of level at N and P is the difference of pressure between the extreme ends of VQ, very approximately.

Now let T be turned fully open, then the tops of the water columns will lie in some irregular line, such as OABCP, and the slope of the line will represent the *fall of pressure* in that particular portion of VQ. Thus, for instance, the slope of OA is much greater than that of AB, indicating that the *loss* or *fall of pressure* in Q is much greater than that in R. In other words, *for a given flow the fall or loss of pressure is proportional to the cross section of the pipe.* It will also be obvious that *the total fall of pressure or head is equal to the sum of the several individual falls*, and of course it is this which causes the flow to take place against the opposition offered by the friction of the pipe.

If the portion Q, say, be of uniform bore, the pressure difference between its ends, namely, AK, is directly proportional to the frictional resistance of that length Q, *i.e.* to the length. Moreover, the stream or quantity of water (in gallons per minute, say) is exactly the same at all points in VQ, though the velocity of the stream in S and Q will be greater than in the large sections V and R.

If, now, instead of the pipe VQ being of varying cross section it was quite uniform throughout, everything else being the same, then when T was fully open the tops of the columns of water would all lie in the straight line ODEFP, indicating that the fall of pressure is directly proportional to the length of a pipe of uniform bore. Lastly, if VQ were still uniform and T partly shunt, the slope of the line OP

would alter to OGHIJ and finally become zero, *i.e.* take the position ON on T being completely closed.

The foregoing effects are extremely analogous to those obtained with a current of elecricity in a circuit, as will be observed by a reference to Fig. 11.

Let W be some convenient source of electricity capable of sending a constant current through the circuit PH, which is of non-uniform cross section as shown and corresponds to the pipe VQ (Fig. 10).

A switch (as it is called) T enables the current to be cut off or otherwise, and corresponds to the tap T (Fig. 10). Now the point H will be at a certain pressure or *potential* (as it is now called) represented by HO say, which is equal to PN.

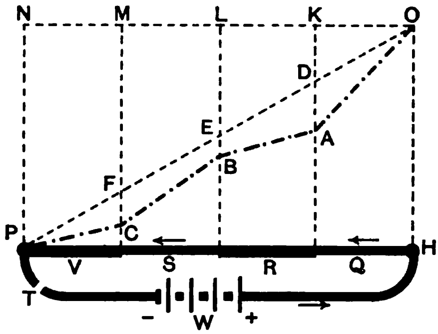


FIG. 11 —Fall of Pressure in an Electric Circuit.

If T is turned off and no current flows, then it can be shown that all points in PH are at the same potential OH, as indicated by the line ON being horizontal; and if T is turned on and a current flows, then OH is the same as before, but the potential at P has fallen to zero. Consequently the difference of potential between P and H is equal to OH, and this causes the flow to take place. We also notice that the potential falls here, as in the case of the water, as we proceed in the direction of flow, and that it is represented by the irregular line OABCP; the greater slope of OA than AB showing that the loss or fall of potential along Q is greater than along R, which has the greater section.

Therefore the smaller the cross section the greater the fall of potential for the same flow or current.

Since the slopes of different parts of the line OABCP are proportional to the section of the various parts of VQ, the total fall between P and H is equal to the sum of the falls in V, S, R, and Q.

If PH were quite uniform in section, then the fall of potential will be given by the straight line ODEFP, showing that *for a constant current the fall or loss of potential is directly proportional to the length for uniform cross section.*

This loss or fall of potential between two points is therefore the same thing as the potential difference between or across them, and which is usually denoted by the letters PD. We have already seen

that when T is open no current flows, and the potential is uniform at all points in PH. Hence an electric current will always flow along a conducting path between any two points which are at different potentials.

Throughout this work we shall denote the *extreme difference of potential* or pressure of any circuit by the term *electro-motive force* (abbreviated commonly to *E.M.F.*), and that between any other two points, which of course must be lower, by *potential difference* (*P.D.*). For instance, the magnitude of the potential at the $+^{ve}$ end of the source W above zero is the *E.M.F.* of this source or of the circuit (Fig. 11), but the *potential of the* $+^{ve}$ *above the* $-^{ve}$ end of W is the *P.D.* of the circuit.

Though the foregoing analogy is an extremely useful and instructive one for explaining the complex phenomena of electric potential, there is one discrepancy that should not be lost sight of, which goes to show that the analogy must not be pressed too far. It is, that a bend in a water-pipe causes a serious increase in the fall of hydraulic pressure, whereas no such increase or effect is produced with the fall of electric potential by a bend, however sharp, in an electrical circuit conveying a steady continuous current.

Having now put before the reader explanations which should enable him to form a clear conception of the extremely important phenomena of electric potential, it only remains for us to define the unit in terms of which it is usually measured.

The practical *unit of potential difference* is called a '*volt*,' and may be defined as *that difference of potential which must be maintained at the ends of a circuit of* 1 *ohm resistance in order that a current of* 1 *ampere may pass through the circuit.*

We shall see presently how the practical units of current, quantity, resistance, and pressure are related numerically in another system of units yet to be dealt with. Certain practical units, however, derived from those of current, resistance, and pressure, must now be considered; but before this can be done it will be desirable to define some commonplace terms employed in physical science, and which are closely related to such derived units.

Matter—Mass—Density.—By *matter* is to be understood anything that produces resistance; and in each of its three possible forms or conditions—viz. solid, liquid, and gaseous—it offers resistance to the motion of anything else.

Mass is the term applied to the amount of matter contained in any body, and commercially it is always measured by weight. In this country the commercial unit of mass is the *pound* (lb.) avoirdupois; and

when speaking of a pound of anything we infer by the word '*pound*' a definite quantity of matter, and that any body having this weight will have the same mass.

The mass of a body does not depend altogether on its size, but also on the denseness with which its molecules are packed, *i.e.* on what is termed its *density*. For instance, there is more matter in a cubic inch of iron than in one of cork, though both have the same size precisely. This is due to the *density* of iron being many times greater than that of cork. Weight being a measure of mass, it would seem that they are practically the same thing. This, for reasons to be stated presently, is not, however, the case.

Force.—This is an attribute of matter, apart from which it cannot be said to exist, in just the same way that an electric current has no existence apart from the conducting path through which it is flowing. From this it will be evident that force, like electricity, can only be measured and dealt with by its effects, and these comprise all the various phenomena which matter exhibits. The most general of these being motion, and as all matter is imbued with a *tendency* to motion, we shall understand by the term *force—anything that produces or tends to produce motion, or change of motion, in matter.* Thus when anything commences to move or stops, or while in motion alters either its direction of motion or speed, *a force* is said to be acting on it.

Now there are many different kinds of force, such as *gravitation, heat, electricity, cohesion, muscular, chemical, mechanical, magneto-motive, and electro-motive forces,* and others. Of these the *force of gravitation* is the most important, being, as it is, ever present in all matter, and in virtue of it all matter tends to fall towards, or, more strictly speaking, is attracted towards, the centre of the earth. The effect of heat is well known in causing forces to act, such as in producing wind, which in turn acts with a certain force.

Electro-motive force we have seen (p. 49) is the force producing or tending to produce a current of electricity. Similarly, magneto-motive force (p. 133) is the force tending to produce magnetism by creating lines of magnetic force. Chemical force may be instanced by the firing of a gun, the charge of powder undergoing chemical change resulting in the exhibition of great force. The force exerted by an engine in drawing a truck, by reason of the force of expansion of the steam on the piston, is an instance of mechanical force; and lastly, the action of the human or animal frame in moving itself or actuating other matter is an example of muscular force.

A little consideration will show us that there is a close connection between many of the different kinds of forces; for instance, the

mechanical force exerted by an engine results from the heat applied to the water in its boiler, while the chemical force present in the explosion of a charge of gas in the cylinder of a gas- or oil-engine produces mechanical force, and is itself the direct result of the effect of heat and chemical reaction.

Returning for a moment to the force of gravitation, it has been mentioned that it is ever present in all matter. We may now add that it gives rise to the phenomenon known as *weight*, and that it explains the tendency of all bodies, near the earth, to fall. Force, therefore, being always present in the form of weight, weight becomes a convenient standpoint or gauge from which to reckon other forces; for instance, any other force can be estimated by seeing what weight would produce the same effect in the same time.

The *unit of force* adopted in this country may be defined as *that force which acting for* 1 *second will give to* 1 *pound of matter a velocity of* 1 *foot per second.*

The magnitude of this unit of force is $\frac{1}{32 \cdot 2}$ of a lb., *i.e.* approximately $\frac{1}{2}$ an ounce avoirdupois; for since 1 lb. of matter in falling freely for 1 second attains a velocity of 32·2 feet per second, the weight of 1 lb. is equivalent to 32·2 units of force, *i.e.* to 32·2 *poundals.*

Weight and Mass.—We have already said that *mass* is the term used to denote the amount of matter in a body; and by weight we understand a certain force of gravitation, which is found to vary inversely with the square of the distance from the earth's centre.

This, then, is sufficient to show us that while a certain body *always* possesses *the same mass*, no matter where it is, the weight of it will vary with its position. Now the earth being somewhat of the shape of a slightly flattened orange, instead of truly spherical, the distance from its centre to the surface is greater at the Equator than at the Poles, since the Poles are situated at the flattened parts. Hence the force of gravity, and consequently the weight, of any given body is a little less at the Equator than at the Poles, though its *mass* is precisely the same at both places.

This small difference, however, could only be detected by weighing on a delicate spring balance, for the weight of an ordinary oscillating balance would alter in the same proportion to the body weighed, and therefore no difference could be detected.

Now, velocity being defined as so many feet per second, the *rate of change of velocity*, called *acceleration*, will be represented by so many feet per second per second.

The acceleration of bodies falling freely under the action of gravity

is approximately 32·2 feet per sec. per sec., which consequently varies at different parts of the earth. This enables us to obtain a more concrete idea of the difference between mass and weight. Thus, let W be the weight of a body of mass M, and g the acceleration due to gravity.

Then $$W = Mg.$$

Hence the weight of a body will form a true measure of its mass only when the force of gravity is constant.

To take one or two examples:—

Example 1.—Find the mass of a body whose weight is 321·9 lbs. at a place where the acceleration due to gravity is 32·19 feet per sec. per sec.

Taking the above relation $W = Mg,$

we have the mass $M = \frac{W}{g} = \frac{321 \cdot 9}{32 \cdot 19} = 10.$

Example 2.—If the mass of a body is 100 where the acceleration due to gravity = 981·2 cms. per sec. per sec., what is its weight?

Here $$W = Mg = 100 \times 98 \cdot 12 = 98,120 \text{ grammes}.$$

Momentum.—This is a term which applies only to matter in motion, and is usually employed to denote or express the *quantity of motion in a moving body.*

If M be the mass of a body which is moving with a velocity v, then we have that its

$$\text{Momentum} = Mv.$$

The unit of momentum is therefore the quantity of motion in a unit of mass moving with unit velocity. Thus we see that if two bodies are moving with the same velocity, that which has the greater mass will have also the greater momentum. For instance, the momentum of a train heavily ladened and moving with a certain velocity is much greater than the same train *empty*, moving with the same velocity.

Now, since the application of a force is necessary to change the momentum of a body, the more correct *definition of a force* would seem to be *the momentum generated or destroyed in a given time.*

From this we see that a body possessing momentum has a certain amount of energy, in virtue of which it is capable of doing work.

Let us consider an example as illustrating the application of the above relation.

Example.—Compare the momentum of a weight of 100 lbs. moving with a velocity of 32·2 ft. per sec. with that of a weight of 1000 lbs. moving with a velocity of 3·22 ft. per sec.

Now $$W = Mg.$$

$\therefore$ $$M = \frac{W}{g}.$$

Whence the momentum of the first body

$$= Mv = \frac{100}{32 \cdot 2} \times 32 \cdot 2 = 100 \text{ units.}$$

That of the second body

$$= Mv = \frac{1000}{32 \cdot 2} \times 3 \cdot 22 = \frac{1000}{10} = 100 \text{ units.}$$

Hence the momentums are exactly equal.

Work.—*When a force acts on matter in such a way as to change either its position in space or its nature, work is said to be done.*

Since resistance always opposes motion of matter, it follows that a force producing motion does work against resistance, and in fact is necessary to overcome that resistance. But force does not always produce motion in matter and therefore overcome resistance, hence it does not always do work. Thus an engine may exert a very considerable force without moving a train, in which case *no* work is done. Immediately the train is moved, work is done.

In this country, the *practical unit of work is the work done when a body moves through* 1 *foot against a resistance of* 1 *pound* (avoirdupois), and which is called a *foot-pound* (ft.-lb.).

Thus 1 ft.-lb. of work is done when 1 lb. is lifted a distance of 1 ft., or generally if a force of (f) lbs. acts through an effective distance (d) ft.; or, which is the same thing, if a body moves through d ft. against a resistance R lbs., then

$$\text{the work done} = fd \text{ ft.-lbs.} = Rd \text{ ft.-lbs.},$$

the *effective* distance being that in the direction of action of the force or resistance.

To cite an example:—An engine draws a train weighing 100 tons up a gradient of 1 in 100 and 1000 ft. long, what is the work done? Here the resisting force (friction assumed to be negligible) due to gravity acts vertically, therefore the *effective* distance through which the force acts $= \frac{1}{100}$ of 1000 ft. $= 10$ ft.

$\therefore$ $$\text{the work done} = fd = 100 \times 10 = 1000 \text{ ft.-tons}$$
$$= 2240 \times 100 \times 10 = 2,240,000 \text{ ft.-lbs.}$$

Again, to take another familiar example:—The frictional resistance of tram-lines is usually taken at 40 lbs. per ton of tram-car fully loaded. If, therefore, a car weighing 10 tons travels 100 ft.,

$$\text{the work done} = Rd = 10 \times 40 \times 100 = 40,000 \text{ ft.-lbs.}$$

From what has already been said, it will be evident that *the British*

absolute unit of work is the work done by a force of 1 *poundal acting through a distance of* 1 *foot, and which is termed a Foot-Poundal.*

Hence 1 foot-pound = g. foot-poundals,

and 1 foot-poundal is the work done in raising, very approximately, half an ounce through 1 foot.

Now there are several different kinds of work depending on the nature of the force (p. 50) acting, namely—mechanical, electrical, thermal, chemical, magnetic, physical, etc. These are related one to another by a connected system of units, which will be considered later on; it should, however, be remembered that whatever may be the nature of the work done, its equivalent appears in the form of heat.

Now we have considered in sufficient detail work done of a mechanical nature. Every one is familiar with the meaning of physical work resulting from the application of muscular force in overcoming resistance, and of the heating effect caused by it.

Chemical work is done when, for instance, sulphuric acid (oil of vitriol), having the chemical symbol H_2SO_4, is poured into water. Here chemical dissociation, and afterwards combination, takes place, resulting in the production of great heat.

Electrical work is always done whenever a current of electricity flows through a circuit, and the equivalent of such work makes its appearance in the form of heat in the circuit. Often this production of heat is so small, as in the case of the currents employed in telegraphy, etc., that it is unmeasurable with the means so far devised, but it occurs notwithstanding. Now it can easily be shown, experimentally, using suitable apparatus and precautions, that *not only is the heat produced in a conducting circuit, in a given time, proportional to the square of the current strength, but also to the resistance of that circuit.* Or, if C is the current in amperes and R the resistance in ohms through which it flows, then the heat generated is proportional to C^2R.

What is wanted, however, is the actual amount of heat produced in a given time, and this can only be found when we know our unit of heat and the number of such units developed by unit current flowing for unit time through a circuit of unit resistance.

Now the standard *unit of heat* universally adopted in scientific investigations is defined as *the amount of heat required to raise* 1 *gramme* (15·432 *grains or* 0·0022046 *lb. avoirdupois*) *of water from* 0° *C. to* 1° *C.*, and is variously termed a '*calorie*,' '*therm*,' or '*French thermal unit*.'

Also by extremely careful experiment it has been found that

1 ampere flowing through 1 ohm for 1 second generates 0·2390 of such a heat unit.

Hence the actual amount of heat H in heat units or calories produced by a current of C amperes flowing through R ohms for *t seconds* is

$$H = 0{\cdot}2390 C^2 R t \text{ calories.}$$

This is commonly known as *Joule's Law*, and the heating effect as the *Joule effect*.

To cite one or two examples of the application of the formula:

Example 1.—What heat will be generated by a current of 10 amperes flowing through a circuit of 5 ohms resistance for 20 seconds?

Since $$H = 0{\cdot}239 C^2 R t,$$

∴ the amount of heat produced is

$$H = 0{\cdot}239 \times (10)^2 \times 5 \times 20 = 2390 \text{ calories.}$$

Example 2.—Find what current will produce 239 calories in 5 minutes when the resistance is 10 ohms.

Transposing the above relation we have

$$C^2 = \frac{H}{{\cdot}239 \,.\, Rt} = \frac{239}{{\cdot}239 \,.\, 10 \,.\, (5 \times 60)} = \frac{1000}{3000} = 0{\cdot}333.$$

∴ the current $C = \sqrt{{\cdot}333} = 0{\cdot}578$ ampere.

If we employ the lb. and minute instead of the gramme and second respectively in defining the unit of heat, *i.e.* if we take as our unit of heat the heat required to raise 1 lb. (avoir.) of water from 0° to 1° C., then C amperes flowing through R ohms for *t minutes* give

$$H = \frac{60 \times 0{\cdot}239}{453{\cdot}596} C^2 R t = 0{\cdot}0316 C^2 R t \text{ heat units,}$$

where 1 lb. (avoir.) = 453·596 grammes and 1 minute = 60 seconds.

But J. P. Joule, the founder of this law, and subsequently a number of other experimenters, have, by extremely careful and laborious research, shown that this last-named heat unit, *i.e.* the heat required to raise 1 lb. of water from 0° C. to 1° C., is equivalent to 1400 ft.-lbs. of work. Hence the total work (W) in ft.-lbs. done by a current of C amperes flowing through R ohms for *t* minutes is

$$W = 1400 \times 0{\cdot}0316 C^2 R t = 44{\cdot}24 C^2 R t \text{ ft.-lbs.}$$

As an example:—

What work will a current of 10 amperes flowing through a circuit of 5 ohms resistance do in $\frac{1}{3}$ of an hour?

Since $$W = 44{\cdot}24 C^2 R t,$$

we have the work done

$$W = 44{\cdot}24\,.\,(10)^2\,.\,5\,.\,(\tfrac{1}{3}\times 60)$$
$$= 4424\,.\,100 = 442{,}400 \text{ ft.-lbs.}$$

Power.—By *power* is meant *the rate of doing work*, which clearly refers to work done in connection with *time*, whereas work itself has no reference to time. It is therefore most important to clearly distinguish between *power*, *i.e.* rate of doing work, and the amount of *work done*.

An analogy will make this difference clearer. Thus, suppose a certain engine A is able to draw a particular train—the *total* weight of which, including engine, = W tons—a distance D feet in 10 minutes, the resistance opposing motion being 15 lbs. per ton of train; and that another engine B, of the same weight as A, can draw the same train over that same distance D against the same resistance per ton in 5 minutes. Then B is manifestly more powerful than A, because it can do the journey in half the time. The actual total amount of work done is precisely the same in both cases, and = 15WD **ft.-lbs.**; the *power* or *rate of working* (*i.e.* work done per unit of time) is not, however, the same in the two cases, being

$$\text{for engine A} = \frac{\text{total work done}}{\text{total time}} = \frac{15W\,.\,D}{10} = 1{\cdot}5WD \textbf{ ft.-lbs. per minute,}$$

$$\text{and for engine B} = \frac{15W\cdot D}{5} = 3WD \textbf{ ft.-lbs. per minute,}$$

which is clearly twice the former result, and this is expressed by saying that the *power* of B is twice that of A.

We therefore see that the amount of *work done is reckoned in ft.-lbs.*, and *power* or work per unit of time *in ft.-lbs. per minute*.

Now mechanical power is usually estimated in terms of a unit called a '*horse-power*,' which in this and several other countries is taken to be a rate of working equal to 33,000 ft.-lbs. per minute. This, however, is undoubtedly greater than the working capabilities of an average horse.

Electrical power, or rate of working, is measured in terms of a unit called a watt, which is defined as the electrical power expended on a circuit when 1 ampere flows through it at a pressure of 1 volt, or, in a circuit of 1 ohm resistance when 1 ampere flows through it.

If, therefore, the work done in an electrical circuit in t minutes is

$$W = 44{\cdot}24C^2Rt \text{ ft.-lbs.,}$$

electrical power is being expended on the circuit at the rate of $44{\cdot}24C^2R$ ft.-lbs. per minute, whence the electrical horse-power

$$\text{E.H.P.} = \frac{44{\cdot}24C^2R}{33000} = \frac{C^2R}{746} = 0{\cdot}00134C^2R.$$

Further, since it can be shown (p. 65) that $C^2R = CV$, both terms representing watts, where $V =$ the pressure in volts at which the current C amperes flows,

$$\therefore \qquad \text{E.H.P.} = \frac{44{\cdot}24C^2R}{33000} = \frac{44{\cdot}24CV}{33000} = \frac{CV}{746} = 0{\cdot}00134CV;$$

and this is true, in all cases, of a steady current flowing through any circuit whatsoever, and without reference to what the circuit consists of.

From the above we therefore see that a watt is the electrical power developed in a circuit when 44·24 ft.-lbs. of work are done per minute, and that 1 E.H.P. = 746 watts.

Take two or three examples of the application of the above relations:—

Example 1.—What horse-power will be absorbed in a circuit of 74·6 ohms resistance, through which a current of 10 amperes is passing?

Since $$\text{E.H.P.} = \frac{C^2R}{746},$$

we have H.P. absorbed in heat $= \frac{C^2R}{746} = \frac{10^2 \times 74{\cdot}6}{746} = 10.$

Example 2.—If 746 amperes are flowing through a circuit at the terminals of which 100 volts is maintained, what is the H.P. absorbed in the circuit?

Here $$\text{E.H.P. absorbed} = \frac{CV}{746} = \frac{746 \times 100}{746} = 100.$$

Example 3.—Find the potential difference at the terminals of a circuit in which 10 H.P. is absorbed, when a current of 37·3 amperes passes through it.

Since $$\text{H.P.} = \frac{CV}{746},$$

$$\therefore \qquad V = \frac{746 \times \text{H.P.}}{C} = \frac{746 \times 10}{37{\cdot}3} = 200 \text{ volts}.$$

The *unit of electrical work* done in a circuit is termed a '*joule*,' which therefore = 1 watt per second.

$$\therefore \qquad 1 \text{ joule} = \frac{44{\cdot}24}{60} \text{ ft.-lbs.} = 0{\cdot}7373 \text{ ft.-lb.}$$

Energy.—*The energy of matter is its power of doing work*, and energy must always be expended in order that work may be done. All matter is imbued with energy in one or other of two kinds, called—(1) *Kinetic Energy*; (2) *Potential or Latent Energy.*

The former is possessed by all moving matter, and as an instance we may cite the wind (gaseous matter) which moves (blows) against the windmill and so does work in turning it for grinding corn and other purposes.

Now the kinetic energy of a mass M, whose weight is W, and which is moving with a velocity v, can be expressed in terms of this rate of motion. For let d be the distance travelled at a velocity v,

then the $$\text{acceleration } a = \frac{W}{M},$$

and $$v^2 = 2ad;$$

$\therefore$ $$v^2 = 2\frac{W}{M}d,$$

or $$Wd = \tfrac{1}{2}Mv^2 = \text{work done.}$$

The term $\frac{1}{2}Mv^2$ is the kinetic energy of the mass M, and is the number of units of work stored up in that mass.

Potential energy is the latent or stored-up energy of a body in virtue of its position while at rest. The tendency of an elevated body to find a lower level is a good example of potential energy; for so soon as the forces which keep it in position cease to act, its potential energy is immediately converted into kinetic energy and the body falls to a lower level.

From the foregoing remarks it will be evident that energy and work can be measured in terms of the same kind of unit.

Electrical energy is measured in terms of a unit called a '*watt-hour*,' which is equal to the power corresponding to 1 watt acting for 1 hour. In other words, a watt-hour is the electrical energy expended in a circuit carrying 1 ampere at a pressure of 1 volt for 1 hour.

This unit is too small for many purposes at the present day, so that for commercial purposes a much larger unit is adopted called a '*kilowatt-hour*' or '*Board of Trade unit*' (B.O.T. unit), and which = 1000 watt-hours.

It is in terms of this B.O.T. unit that the electrical energy supplied to consumers is measured.

Hence in any circuit carrying a steady continuous current, the maximum value of which occurs simultaneously with that of the pressure at any and every instant, the total electrical energy supplied $= \frac{\text{amperes} \times \text{volts} \times \text{hours}}{1000}$ B.O.T. units.

Summarising the relations which exist between Energy, Power, Work, and Force, we have :—

$$\begin{aligned} \text{Energy} &= \text{Power} \times \text{Time}. \\ \text{Power} &= \text{Work} \div \text{Time}. \\ \text{Work} &= \text{Force overcome} \times \text{Distance}. \end{aligned}$$

At this point we may enunciate a most important fundamental law of physical science known as the law of the *conservation of energy*, namely :—

1. *Energy can never be lost or destroyed.*

2. *Each form of energy can be converted into any other form*, from which it follows that the total amount of energy in the universe never alters in amount.

The reader is strongly recommended to commit these propositions to memory, and by keeping them before him he will be able to understand more easily many phenomena met with in electrical engineering.

Absolute System of Measurement.—We have, up to the present, been considering a system of measurement based on definitions and units which have been chosen quite arbitrarily. This is known as the '*practical*' system. There is, however, another system, closely related to the above, which has the great advantage of being based on three fundamental quantities or units only—*Length*, *Mass*, and *Time*. In this system, then, the fundamental *unit of length* is the *centimetre* (cm.) = 0·39370 of an inch, or $\frac{1}{10^9}$th of the length of an earth quadrant.

Unit of mass is the *gramme* (grm.) = 15·4323 grains, and is the mass of 1 cubic centimetre of pure water at its point of maximum density, namely, 4° C.

Unit of time is the *second* (sec.) = $\frac{1}{86164}$th of a sidereal day. The system of units *derived* from these three fundamental standards of length, mass, and time is often termed an *absolute* system, because it is entirely based on these three arbitrary units, which are capable of being accurately reproduced at any time, and is in no way dependent on the value of gravity, on the form of any particular apparatus, or on any other arbitrary quantity.

The system, which is universally recognised, is usually termed the *Centimetre-Gramme-Second* (abbreviated to *C.G.S.*) system of units, and possesses many advantages over the British *Foot-Pound-Second* (*F.P.S.*) system which we have already considered. For instance, the C.G.S. system is a decimal one; and, further, the units of length and mass are directly related by reason of the fact that the weight of 1 cubic centimetre of pure water at 4° C. = 1 gramme.

We will now consider the units of this absolute C.G.S. system.

ABSOLUTE C.G.S. SYSTEM

Fundamental arbitrary units—

Length: the centimetre (cm.).
Mass: the gramme (grm.).
Time: the second (sec.).

Derived mechanical units—

Area: the square centimetre (sq. cm.).
Volume: the cubic centimetre (c.c.).

Velocity.—When a body moves through unit distance in unit time, *i.e.* at the rate of 1 cm. per sec., it is said to have unit velocity.

Acceleration.—When a body acquires or loses unit velocity in unit time it has unit acceleration or retardation, respectively, *i.e.* a rate of 1 cm. per sec. per sec. The acceleration due to gravity, which varies slightly with different latitudes, is 978·10 cms. per sec. per sec., or 32·091 ft. per sec. per sec. at the Equator; these numbers becoming respectively 981·17 or 32·191 in London, and 983·11 or 32·252 at the North Pole.

Force.—Unit force is that force which, acting for a second on a mass of 1 gramme, gives to it a velocity of 1 cm. per sec. This unit is termed a *dyne*, and it is therefore the force with which a weight equal to $\frac{1}{981}$ of a gramme (approximately) gravitates. It follows therefore that a weight of 1 gramme gravitates with a force of 981 dynes approximately, or one grain with a force of $\frac{981}{15 \cdot 432} = 63 \cdot 57$ dynes.

Energy and Work.—These are measured in terms of the same unit, since the work which a body is able to do is a measure of its energy.

The unit of work is that done by a force of 1 dyne acting through a distance of 1 cm. and is called an *erg*. From this definition and the above it follows that 981 ergs of work are done when 1 grm. rises or falls vertically through a distance of 1 cm.

Systems of Electrical Units.—From the foregoing C.G.S. system of fundamental units, two important systems of electrical units are derived. One, known as the electro-static system, originates from the relation given on p. 25, in connection with the force exerted between two quantities of electricity. The other is known as the electro-magnetic system, and originates from the relation given on page 15, in connection with the force exerted between two magnetic poles.

This latter system, in which the strengths of currents, etc., are expressed in magnetic measure, is evolved from the system of magnetic units, which is itself derived from the fundamental units of length, mass, and time. A detailed discussion here of the two systems mentioned above is, however, outside the scope of this work, and for such the reader should refer to, for instance, Maclean's *Physical Units.*

It is important to remember that the electro-magnetic system of C.G.S. units is the one which concerns us most in the present case, and we may therefore pause to say a few words about it.

In this system the units are determined in the following order:—(1) unit pole, (2) current, (3) quantity, (4) potential difference or E.M.F., (5) resistance, (6) capacity.

The first-named or unit pole has already been defined on page 15, from the relation $F \propto \frac{m_1 m_2}{d^2}$.

2. *Unit Current.*—The C.G.S. unit of current is obtained from the following considerations. Let the pole m_1 in the above relation be acted on by a current (C) flowing through a circuit, a portion of which is bent into the arc of a circle of radius (d), and having m_1 at the centre.

Then the current C now acts electro-magnetically on m_1, taking the place of m_2; and the above relation still holds if we put $Cl = m_2$, for the magnetic effect of C will evidently depend on the length of arc (l). Substituting, we have

$$F = \frac{m_1(c \,.\, l)}{d^2},$$

or

$$C = \frac{Fd^2}{m_1 l}.$$

Making F, d, m_1, and l each unity, we obtain our definition for unit current as follows:—

A C.G.S. unit of current is that which exerts a force of 1 dyne on a unit magnetic pole placed at the centre of an arc of its circuit 1 cm. long and 1 cm. radius.

3. *Unit Quantity.*—A C.G.S. unit of quantity is that which, in one second, is conveyed by this C.G.S. unit of current.

4. *Unit Potential Difference or E.M.F.*—We have already observed (p. 55) that when a current C flows through a circuit under an E.M.F. or potential difference V, a certain amount of work (w) is done per second; or that

$$w \propto CV.$$

Consequently a C.G.S. unit of P.D. or E.M.F. is that which exists between any two points of a conductor conveying a unit current, when 1 erg of work is done per second.

5. *Unit Resistance.*—A C.G.S. unit of resistance is that possessed by a conductor in which unit E.M.F. causes unit current to flow.

6. *Unit Capacity.*—A C.G.S. unit of capacity of a condenser is that obtained when unit quantity in either coating produces unit P.D. between them.

Now for practical purposes large multiples of the above *absolute* electro-magnetic C.G.S. units have to be taken in some cases, and in others small fractions. This is necessitated by the C.G.S. units of E.M.F. or P.D. and resistance being extremely small, as found by the above definitions, that of capacity being extremely large, while those of current and quantity are a little too large for practical purposes.

About 1863, therefore, a select committee of the British Association chose a practical system of units based on the absolute electro-magnetic system, so that the fundamental laws held equally for both. In this case, however, the fundamental units of length, mass, and time adopted were 10^9 cms. (an earth quadrant), 10^{-11} gramme, and the second in the C.G.S. system.

The relation between practical and absolute C.G.S. units in the electro-magnetic system is as follows :—

TABLE IV

	Name of Electrical Unit in Practical System.	Equivalent of Practical Unit in Electro-magnetic C.G.S. Units.
Current	Ampere	10^{-1}
Quantity	Coulomb	10^{-1}
Potential	Volt	10^8
Resistance	Ohm	10^9
Capacity	Farad	10^{-9}
Power	Watt	10^7
Work	Joule	10^7
Induction	Weber	10^8
Self-Induction	Secohm	10^9
Mutual-Induction	,,	10^9

Note.—The numbers in the third column of the table are usually written in this form for convenience, but it may be remarked that the index in all cases represents the number of ciphers following 1. Thus $10^{-1} = \frac{1}{10} = 1$ tenth.

$10^8 = 100{,}000{,}000 = 1$ hundred million.

$10^{-9} = \frac{1}{1000000000} = 1$ thousand-millionth.

We shall now briefly indicate the relations that exist between the various units commonly met with in practice.

LENGTH

1 millimetre	= 0·001 metre	= 0·03937 inch.	
1 centimetre = 10 millimetres	= 0·01 ,,	= 0·3937 ,,	
100 centimetres = 1000 ,,	= 1 ,,	= 39·37 ,,	
1 kilometre	= 1000 metres	= 39370 ,,	
1 inch	= 2·54 centimetres.		
1 foot	= 30·4797 ,,		

1 circular mil = area of a circle of one mil (= 0·001 inch) diameter.

MASS

1 milligramme =	0·001 gramme =	0·015432 grain.	
	1 ,, =	15·432 grains	= 0·0022046 lb. avoir.
1 kilogramme = 1000 grammes	= 15,432 ,,		= 2·204 ,,
1 lb. (avoir.) = 453·596 grammes	= 0·45359 kilogramme.		

Area and Volume

1 square centimetre = 0·155 square inch.
1 ,, inch = 6·451 ,, centimetres.
1 cubic centimetre = 0·061 cubic inch.
1 ,, inch = 16·387 ,, centimetres.
1 litre = cube of 10 cm. edge = 1000 cubic cms. = 61·027 cubic ins. = 1·760 pint.

Force

1 dyne = weight of $\frac{1}{981 \cdot 17}$ gramme in London.
1 poundal = 13,825 dynes.
1 poundal = weight of $\frac{1}{32 \cdot 191}$ lb. (avoir.) in London.

Work and Energy

1	ft.-lb. =	$1 \cdot 356 \times 10^7$ ergs =	1·356 joule =	0·138 kilogrammetre.
$7 \cdot 37 \times 10^{-8}$	,, =	1	,, = 10^{-8}	,, = 10^{-9} ,,
0·7373	,, =	10^7	,, = 1	,, = 0·102 ,,
7·233	,, =	$98 \cdot 1 \times 10^6$	,, = 9·81	,, = 1 ,,

1 foot-pound = g foot-poundals = 13,825 gramme-centimetres.
1 foot-poundal = 421,390 ergs.

Power

$$1 \text{ H.P.} \begin{cases} = 33{,}000 \text{ ft.-lbs. per min.} = 550 \text{ ft.-lbs. per sec.} \\ = 746 \text{ joules per sec.} = 746 \text{ watts.} \\ = 76 \text{ kilogrammetres per sec.} = 746 \times 10^7 \text{ ergs per sec.} \end{cases} = 1 \text{ E.H.P.}$$

1 French H.P. = 75 kilogrammetres per sec. = 542 ft.-lbs. per sec. = 736 watts = 0·9863 English H.P.

$$1 \text{ watt} \begin{cases} = 0 \cdot 7373 \text{ ft.-lb. per sec.} = 10^7 \text{ ergs per sec.} \\ = 1 \text{ joule per sec.} = \frac{1}{746} \text{ H.P.} \\ = 0 \cdot 1029 \text{ kilogrammetre per sec.} = 0 \cdot 00134 \text{ H.P.} \end{cases}$$

1 commercial unit of electrical power = 1 kilowatt = 1000 watts.

Energy

1 Board of Trade unit of electrical energy = 1 kilowatt-hour = 1000 watt-hours = 1·34 H.P.-hours.

Heat and Work

1 calorie (French thermal unit) = 1 gramme-degree Cent. = 4·184 joules
= $4 \cdot 184 \times 10^7$ ergs = 3·086 ft.-lbs.
= 0·00396 of a British thermal unit.
1 (British thermal unit) = 1 lb.-degree Fah. = 251·9 calories.
= 1060 joules = 1060×10^7 ergs.
= 777·7 ft.-lbs. at Greenwich.
1 joule = 0·239 calorie.
= 1 watt per sec.

QUESTIONS ON CHAPTER III

[*Supplement all Answers with Sketches when possible.*]

1. Enumerate the properties or effects produced by an electric current, and give familiar instances of the commercial application of each.
2. Define the terms cathode, anode, electrolyte, electro-chemical equivalent.
3. Give the definition of the practical units of current, resistance, potential, and quantity, and also their equivalents in the C.G.S. system of units.

4. If 100 coulombs of electricity pass through a circuit in 1 minute, what is the current strength?

5. Find the current that will carry 3600 coulombs of electricity through a circuit in half an hour.

6. Define an ampere, 10,000 volts, 1 megohm, a kilowatt, 40 Board of Trade units, and 100 horse-power. (Prelim. 1897.)

7. What is meant by 'absolute' units?

8. Write down the terms Work, Force, Power, Quantity as headings, and then arrange the names of the following units each under its proper heading:—watt, kilowatt, ampere-hour, horse-power, dyne, kilowatt-hour. (Prelim. 1902.)

9. Define shortly electro-motive force, resistance, and current. (Prelim. 1902.)

10. How many horse-power are required to drive a dynamo lighting 1200 lamps, each taking 0·3 ampere at 200 volts (combined efficiency of dynamo and circuit 90%)? (Prelim. 1902.)

11. What weight of copper will be deposited in a copper voltameter by a current of 20 amperes flowing for 1 hour (z for copper = 0·0003279)?

12. Find the current that will deposit 5 grammes of silver in a silver voltameter in 20 minutes (z for silver = 0·0011180).

13. What do you mean by electrical pressure and potential difference? Give the unit in terms of which they are measured.

14. In drawing a train weighing 200 tons an engine overcomes a tractive resistance of 15 lbs. per ton. If the train travels 10 miles, what work does the engine do?

15. In the last question, if the same train travels up an incline of 1 in 300 for a distance of 2 miles instead, what work is done, with the same resistance?

16. If 20 amperes flow through a circuit of 10 ohms resistance for 1 hour, find (1) the heat generated, (2) work done in the circuit, (3) power absorbed.

17. What will be (1) the heat generated, (2) work done, in a circuit in which a current of 100 amperes causes 50 E.H.P. to be absorbed in 2 hours?

18. If a weight of 1 ton acquires a velocity of 2 miles an hour, what is its kinetic energy?

19. How are the 'practical' and 'absolute' systems of units related? Give instances in several cases.

20. Define the exact relation of the watt to the coulomb. (Elec.-Metall. Ord. 1897.)

21. What is Faraday's law regarding electro-deposition? How much caustic soda is produced per ampere-hour, and how much lead, silver, and mercury (from mercurous nitrate) would be deposited per ampere-hour? One coulomb evolves, say, 0·104 milligramme of hydrogen, and the atomic weights of sodium, lead, silver, and mercury are respectively 23, 207, 108, and 200. (Ord. 1899.)

22. Define a kilowatt and a Board of Trade unit of energy. Explain clearly the difference between them, and describe in detail, with sketches, the instruments which are commercially employed in measuring these two quantities. (Prelim. 1900.)

23. What do you mean by 'absolute' units? (Ord. T. and T. 1900.)

24. Write equivalents of the following quantities in the international units based on the centimetre, the gramme, and the second:—1 inch, 1 square inch, 1 yard, 1 cubic yard, 1 pound, 1 foot-pound, g, 1 horse-power-hour, 1 gallon.

25. If a man supports a weight of 10 lbs. for 17 minutes, does he do any work? If so, how much? (Prelim. 1895.)

26. Define a foot-pound, poundal, dyne, and kilogrammetre, and state how they are related. (Ord. 1895.)

27. Define the terms watt, joule, coulomb, Board of Trade unit, as applied in electric measurement. Distinguish between work and power. Is a foot-pound a unit of work or power? (Ord. 1900.)

CHAPTER IV

ELECTRICAL RESISTANCE

REFERENCE has already been made to the fact that matter in each of its three states—solid, liquid, or gaseous—invariably introduces an obstruction, or, in other words, offers a resistance to the passage through it of an electric current of any description or magnitude. This is strikingly analogous to the resistance which matter in each of the above forms offers to the motion of any body through it.

The origin and definition of the unit in terms of which the resistance opposing the flow of an electric current is measured has been dealt with somewhat in detail in Chapter III. page 43.

Further, we have seen that an electric current cannot flow unless a difference of electric potential exists, and neither can a current flow without encountering some resistance. Now *any* path traversed by an electric current may be called an *electric circuit*, whether such a path be solid, liquid, or gaseous, or any combination of these. Thus in *any* electrical circuit there are always two other factors—*pressure* and *current*—to be considered in addition to resistance.

Ohm's Law.—As a result of the above considerations, Dr. G. S. Ohm first enunciated, in the early part of last century, a rule connecting *resistance*, *current*, and *pressure* in a circuit. The accuracy of this rule was confirmed beyond all doubt some years ago by a most careful and elaborate series of tests made at Cambridge, and it may be stated as follows:—*For any metallic conductor at constant temperature the ratio of the P.D. at its terminals to the corresponding current flowing through it is absolutely a constant for all values of current.* This ratio is the '*resistance*' of the conductor.

Thus we have

$$\text{Resistance} = \frac{\text{Terminal P.D.}}{\text{Current}},$$

which is called *Ohm's Law*, and is a fundamental law of the greatest importance, for but few problems in current electricity can be solved without its aid. In the above form, however, it is only applicable

for use in the case of resistances or circuits in which all the electrical energy supplied to them is transformed into heat. There are, however, many circuits in which the whole energy supplied is not transformed into heat. Instances of such are circuits containing electrolytic cells (pp. 37 and 410), electro-motors, transformers, etc. These appliances oppose the passage of an electric current by reason of their metallic resistance, and in addition introduce a counter or opposing P.D. to that which causes the current to flow through them.

This is the same effect as would occur in a circuit containing several generators of P.D., some of which were connected with the rest so as to oppose the action of the latter.

Ohm's Law can, however, be stated quite generally, so as to be applicable in the case of *any circuit*, in the following way:—

Let E = the total impressed E.M.F. (p. 49) of the generator.

e = „ counter E.M.F. of any appliances in circuit.

R = „ resistance of the whole circuit, whether partly liquid as well as solid, including the internal resistance of the generator.

Then if C is the current flowing, we have

$$C = \frac{\text{total net or effective E.M.F.}}{\text{total circuit resistance}} = \frac{E - e}{R},$$

or

$$R = \frac{E - e}{C},$$

or

$$E - e = CR.$$

When the circuit has resistance only, and does not contain any appliance which can produce a counter or back E.M.F., then $e = 0$, and our relations above become

$$C = \frac{E}{R},$$

$$R = \frac{E}{C},$$

and

$$E = CR.$$

If the symbols on the right-hand side of each of the preceding equations represent the quantities in practical units (p. 62), then the results or the values of those on the left will also be in practical units.

It may here be pointed out that Ohm's Law, as given above, is rigorously true for continuous or direct currents where R is the total metallic resistance or liquid resistance of the circuit.

For the same circuit used with alternating currents, however, this total resistance may rise to some higher apparent or effective value due to the circuit perhaps possessing electro-static or electro-magnetic inductance. Then for R in the above relations must be substituted

the effective value of the total resistance, when the law will again hold good. If the circuit possesses no inductance of either kind, then Ohm's Law holds for either direct or alternating currents. It is undesirable at the present stage to go further into the exact nature of the increase of resistance which may occur with alternating currents, but it may be mentioned that the same straight solid wire will, if of sufficient diameter, offer greater resistance to alternating than to direct currents, due to the former apparently confining their flow to the outer portions of such a conductor. We shall presently work out some examples (p. 71) showing the application of this law in practice, but for the present it may be well to go a little further into the subject of resistance before doing so.

Variation of Resistance with Length.—That the resistance of a conducting medium varies with the length of path will be evident from considerations met with in Chapter III. By means of Ohm's Law, and by the aid of some simple apparatus, it is easy to determine the relation subsisting between the resistance of a conductor and its length. This is indicated in Fig. 12, in which *ab*, *cd*, and *ef* are three conductors, each of uniform cross-sectional area and of the same material, and say the same length, but differing in section. Suppose these are connected together at the end *ade* and to a delicate detecting instrument capable of measuring the current which an electric generator K sends through it and the rest of the circuit *abr*KG, where *r* is some resistance for keeping the current constant in strength. Let V be an instrument capable of measuring P.D., and which has one terminal connected to *a* and the other to a movable contact P capable of touching *ab* at any point such as P or Q. It will then be noticed that on sending a *constant current* through *ab* the P.D. as read off on V is directly proportional to the distance of the point of contact, such as P, Q, etc., from *a*; or if V_P, V_Q, V_b, . . ., etc., are the readings of V when the sliding contact is at P, Q, *b*, . . ., etc., respectively, then

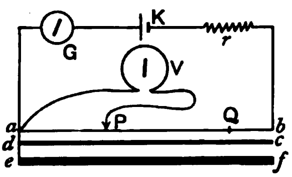


FIG. 12.—Sketch of Conductor and P.D. Measurer for R ∝ L.

$$\frac{V_P}{V_Q} = \frac{aP}{aQ}$$

or

$$\frac{V_P}{V_b} = \frac{aP}{ab}.$$

Now Ohm's Law states that E = CR, where E is the reading of V when connected to the extremities of a resistance R which is carrying a current C. Hence we have

P.D. between a and P = current through aP × resistance of aP,

or $$V_P = C \times R_{aP}.$$

Similarly $$V_Q = C \times R_{aQ}.$$

Hence by division we have

$$\frac{V_P}{V_Q} = \frac{CR_{aP}}{CR_{aQ}} = \frac{R_{aP}}{R_{aQ}} = \frac{\text{length } aP}{\text{length } aQ}.$$

The same result would be obtained if cd or ef had been taken instead of ab, and any other points than P and Q. Therefore we may define our first law of resistance, namely, that '*the resistance of a given conductor of uniform section at a constant temperature is directly proportional to its length.*' Or in symbols, if L is the length and R the resistance, then $R \propto L$, *i.e.* the longer a conductor is, the greater will be its electrical resistance.

Variation of Resistance with Cross-sectional Area.—If, with the same apparatus as depicted in Fig. 12, we connect the equal lengths of conductors ab, cd, and ef successively in circuit, sending exactly the same current, as read off on G, through each, it will be noticed that the P.D.'s, as indicated by V, between the points a and b, c and d, and e and f are not equal, but show the following proportion, namely:—

$$V_{ab} : V_{cd} : V_{ef} = \frac{1}{S_{ab}} : \frac{1}{S_{cd}} : \frac{1}{S_{ef}},$$

where S denotes sectional area.

But for the same current by Ohm's Law we have

$$V_{ab} : V_{cd} : V_{ef} = CR_{ab} : CR_{cd} : CR_{ef} = R_{ab} : R_{cd} : R_{ef}.$$

Hence $$R_{ab} : R_{cd} : R_{ef} = \frac{1}{S_{ab}} : \frac{1}{S_{cd}} : \frac{1}{S_{ef}}.$$

The same proportion would have been obtained by taking any other equal lengths than ab, cd, and ef. Therefore we can define the second law of resistance, namely, that '*the resistance of a given conductor at constant temperature is inversely proportional to its sectional area,*'

or $$R \propto \frac{1}{S},$$

i.e. the thicker a conductor is, the less will be its resistance. Combining this with the first law, we find that

$$R \propto \frac{L}{S}.$$

Variation of Resistance with Material.—We have already mentioned that the resistance of a conductor varies with the material of which it is made, other things being equal, and we shall see later on

that it also varies with the physical condition of the conductor, *i.e.* whether this is hot, cold, hard, or soft, and with its purity, etc.; but by means of the arrangement shown in Fig. 12 this can easily be proved. Thus if *ab*, *cd*, and *ef* are made of *any* three different materials of exactly the same length and sectional area, the reading of V would be different in each case when taken between the extremities for exactly the same current in each wire. This proves that the resistance of a conductor depends on the material of which it is made for a given length and sectional area. Comparisons are made between the various materials by finding the resistance of a mass of perfectly definite and known volume in a particular and definite form. This resistance is a constant for each material at constant temperature.

Now in order that the last equation shall give the value of R in ohms and be one of equality and not merely proportionality, it will be necessary to multiply it by a *constant* for the particular material in use and temperature at the time. This constant is termed the '*specific resistance*,' or sometimes '*resistivity*,' of that material at that temperature, and may be defined as '*the resistance in ohms of unit length of the material having unit cross-sectional area*,' or, in other words, '*the resistance between opposite faces of a unit cube of the material.*' This is sometimes called '*volume specific resistance.*' The unit adopted is both the inch and the centimetre, so that specific electrical resistance is the resistance per inch cube or per cm. cube of the material in ohms, and it is usually denoted by the symbol 'ρ.'[1]

Hence $$R \propto \rho.$$

The values of specific resistance 'ρ' are given in Tables V. and VI. pages 77 and 79, for a number of the most important metals and alloys in use.

Collecting the three rules defined above, we see that

$$R = \frac{L\rho}{S} \text{ ohms},$$

where L and S are both in similar units—inches or centimetres.

This last equation, combined with Ohm's Law, enables us to at once obtain the *fall of potential*, otherwise called '*the drop*,' in any electrical conductor due to its metallic resistance when any given current flows through it.

Thus if a current C amperes flows through a conductor of resistance

[1] The reader should guard against using the term 'ohms per cubic inch' or 'per cubic cm.' for specific resistance. Such is often employed, but is a wrong appellation, seeing that an inch cube or a cm. cube is a perfectly definite thing, whereas a cubic inch or cubic cm. may have any form and therefore any resistance at one and the same temperature.

R ohms, the P.D. at its extremities, *i.e.* the fall of potential down it, or the *drop*, $V = CR$ by Ohm's Law.

But
$$R = \frac{L\rho}{A}$$
if L and A are the length and cross section of the conductor of specific resistance ρ.

$\therefore$ the *drop*
$$V = CR = C\frac{L\rho}{A}.$$

Hence the drop in a conductor is directly proportional to the current and to its length, and inversely proportional to its cross-sectional area; or, for the same current, half the section will give twice the drop.

The loss of power w in the conductor will be
$$w = C^2R = \left(C^2\frac{L\rho}{A}\right) \text{ watts.}$$

The (volume) specific resistance ρ, as defined above, can be determined from a piece of uniform wire of circular section drawn from the given material.

Thus let
$R =$ its resistance in ohms.
$L =$,, length in centimetres.
$D =$,, diameter in centimetres.
$G =$,, specific gravity.
$W =$,, weight in grammes.

Then
$$R = \frac{L\rho}{S} = \frac{4L\rho}{\pi D^2},$$
where
$$S = \frac{\pi D^2}{4}.$$
Hence
$$\rho = \frac{R\pi D^2}{4L}.$$
But
$$W = LGS = LG\frac{\pi D^2}{4},$$
or
$$\pi D^2 = \frac{4W}{LG}.$$
Hence by substitution we have
$$\rho = \frac{R\pi D^2}{4L} = \frac{R4W}{4LLG} = \frac{RW}{L^2G}.$$

Specific electrical resistance can, however, be expressed as the resistance of a known mass of the material, viz. the resistance between the ends of a wire 1 metre long, of uniform circular section, and weighing 1 gramme. This is sometimes called '*mass specific resistance*,' and may be denoted by the symbol ρ_m. This may be expressed in terms of the length in centimetres, mass in grammes, and resistance in ohms of any wire of uniform circular cross section.

Thus $$\rho_m = \frac{10000 \text{ WR}}{\text{L}^2},$$

where $\frac{\text{L}}{100}$ = the length in metres, and the other symbols have the above meaning.

To familiarise the reader with the application of the preceding laws, a few examples will be taken.

Example 1.—A certain current generator, having an internal resistance of 0·5 ohm and a total E.M.F. of 200 volts, supplies an electric circuit having a back E.M.F. of 180 volts, with current through a copper main having a total length of ¼ mile and cross section 0·01 square inch. Find the current strength.

The resistance of the main must first be found from the last equation, and in this we have L = ¼ mile = 0·25 × 1760 × 3 × 12 inches, S = 0·01 sq. in., and ρ = 0·00000067 ohm per inch cube for copper at ordinary atmospheric temperature (15° C.). Hence the resistance of the copper main

$$\text{R} = \frac{\text{L}\rho}{\text{S}} = \frac{\cdot 25 \times 1760 \times 36 \times \cdot 00000069}{\cdot 01} = 1\cdot 093 \text{ ohm.}$$

Whence the current by Ohm's Law is

$$\text{C} = \frac{\text{E} - e}{\text{R}} = \frac{200 - 180}{1\cdot 093 + \cdot 5} = \frac{20}{1\cdot 593} = 12\cdot 55 \text{ amperes.}$$

Example 2.—Find the length of a copper main having a cross section of 0·25 sq. in. and a resistance of 0·5 ohm at 15° C.

Here $$\text{L} = \frac{\text{RS}}{\rho} = \frac{\cdot 5 \times \cdot 25}{\cdot 00000067} = 186{,}567 \text{ inches} = 2\cdot 944 \text{ miles.}$$

Example 3.—What sectional area must a copper main have which is 2 miles long and has to carry 200 amperes with a fall of potential of not more than 20 volts?

By Ohm's Law the resistance of the main must be

$$\text{R} = \frac{\text{V}}{\text{C}} = \frac{20}{200} = 0\cdot 1 \text{ ohm.}$$

Hence the required section is

$$\text{S} = \frac{\text{L}\rho}{\text{R}} = \frac{2 \times 1760 \times 36 \times \cdot 00000067}{0\cdot 1} = \cdot 849 \text{ sq. in.}$$

Example 4.—What will be the resistance of 10 yards of platinoid wire 0·001 sq. in. sectional area at 0° C.?

From the table, page 80, we find that for platinoid ρ = 0·00001643 ohms per inch cube.

Hence the required resistance will be

$$\text{R} = \frac{\text{L}\rho}{\text{S}} = \frac{10\,.\,3\,.\,12\,.\,0\cdot 00001643}{0\cdot 001} = 5\cdot 868 \text{ ohms.}$$

Example 5.—Find the P.D. at the extremities of an electric circuit having 0·1 ohm resistance in order that a current of 100 amperes may flow through it.

By Ohm's Law the P.D. $(V) = CR = 100 \times 0{\cdot}1 = 10$ volts.

Variation of Resistance with Temperature.—In the definition of resistance given in the preceding pages, temperature was mentioned. This arose from the fact that the resistance of any conductor or insulator actually depends on the temperature at any given time, in much the same way that the length of a rod of material depends on the temperature. One reason suggested to explain why change of temperature should alter the electrical resistance of a body is that alteration of temperature causes the molecules of a body to change their positions relatively to one another, thereby causing an expansion or contraction of the body. Thus in a heated substance it is conceivable that the molecules are more tightly packed, causing greater obstruction to the flow of electric current through them. Such an hypothesis must, however, be accepted with reserve, seeing that the electrical *resistance of electrolysable liquids diminishes with rise of temperature*, though such liquids expand with heat as do solids, while the resistance of all the metals and, with very few exceptions, of all the alloys increases. On the other hand, the non-metals (some fifteen in number), such as the gases oxygen, hydrogen, nitrogen, chlorine, bromine, iodine, fluorine, and the solids carbon, sulphur, silicon, boron, arsenic, phosphorus, etc., all show a decrease in resistance for increase of temperature. This is also the case with insulating materials which are made from compounds containing two or more of the non-metals. It will be seen later that this extremely important effect of temperature on the resistance of substances causes certain substances to be pre-eminently suitable for certain purposes. The amount of increase or decrease of resistance in ohms which 1 ohm in any given material would undergo for each degree Centigrade change of temperature is called the coefficient of variation of resistance with temperature for that material, or, more briefly and commonly, the '*temperature coefficient of resistance*' for the material. This is usually denoted by the Greek letter 'α,' and is a constant within a certain range of temperature.

That such a coefficient exists was conclusively shown by Dr. Matthiessen some years ago in a very careful series of tests which he made on the variation of resistance of materials with temperature. His results prove that while the variation of resistance of all pure metals, with the exception of mercury, is not absolutely in direct proportion to corresponding variations in temperature, the two are sufficiently in direct proportion for all practical purposes.

The small difference involves a term containing the square of the temperature. Thus—

If R_0 is the resistance of a body at 0° C.
and R_t ,, ,, the ,, t° C.,

then $R_t = R_0(1 + \alpha t \mp \beta t^2)$ very approximately,

where α and β are constants for any particular material.

β, however, is in most cases very small, amounting only to about 0·00000125 for most pure metals except iron, and to much less in the case of alloys, so that the term βt^2 is small enough to neglect for all practical purposes.

Hence we have $R_t = R_0(1 + \alpha t)$,
where α is the '*temperature coefficient*' of the material.

The values of α for many important metals, alloys, and liquids are given in Tables V. and VI. pages 77 and 79.

The resistance of all elementary metallic substances except carbon increases with rise of temperature.

In other words, the temperature coefficient α is $+^{ve}$, and for most pure metals excepting mercury, nickel, and iron has an average or mean value = 0·00401 between 0° C. and 100° C., which is large.

The individual value of α should, however, be employed in any calculation for the particular material in question. On the other hand, the specific resistance of the elementary substances is low.

As a general rule, the combination of two or more elements to form an alloy results in the alloy having a higher specific resistance and lower temperature coefficient than that of any of its component elements.

For instance, the resistance alloy platinum-silver (p. 80), having a specific resistance of 31·582 microhms per cm. cube and a temperature coefficient of 0·000243, consists of the elementary metals silver (66 %) and platinum (33 %), the specific resistances of which are respectively 1·468 and 10·917 microhms per cm. cube and the temperature coefficients 0·0040 and 0·00367 respectively.

The value of α in certain instances, such as the alloys manganin and eureka, is not only very small, but is $-^{ve}$, *i.e.* the resistance *decreases*, as in the case of carbon, with rise of temperature. This is perhaps one reason for thinking that possibly carbon is not an elementary substance after all.

The alloy manganin has a rather peculiar variation of resistance with temperature, being $+^{ve}$ and decreasing for a certain range, and then $-^{ve}$, as the following figures show:—For 0° to 10° C. $\alpha = +0·000024$; 10° to 20° C. $\alpha = +0·000013$; 20° to 30° C. $\alpha =$

$+0{\cdot}000003$; 30° to 40° C. $a=0$; 40° to 50° C. $a=-0{\cdot}000003$; 50° to 60° C. $a=-0{\cdot}000007$; 60° to 100° C. mean $a=-0{\cdot}000025$.

The last equation may be written in a form which will be more generally applicable in practice, since the resistance R_0 at 0° C. is hardly, if ever, known.

Thus, if R_1 is the resistance at some temperature t_1, and R_2 is the resistance at another temperature t_2,

then $$R_2=R_1\{1+a(t_2^\circ-t_1^\circ)\}.$$

Temperature Coefficient of a Combined Circuit.—It is invariably the case that an electric circuit consists of more than one kind of material, *i.e.* it does not consist of copper throughout. Thus it may comprise copper connecting wires and resistances which may consist of a liquid, or iron, or some alloy.

In certain cases the temperature coefficient of such a circuit might be required, and we will now consider how the combined temperature coefficient may be found in the case of a circuit composed of two or more materials having different temperature coefficients.

First, consider the case of two resistances joined 'end on' to one another, or, as it is more technically termed, connected *in series* with one another. The arrangement is shown symbolically in Fig. 13,

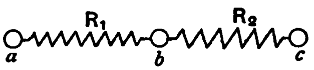


FIG. 13.—Two Resistances in Series.

where ab is one material having a resistance R_1, and bc the other, of resistance R_2. Further, let a_1 and a_2 be the respective temperature coefficients of R_1 and R_2. Required that of the combination R_1+R_2, *i.e.* the temperature coefficient a between the points a and c. From the definition of temperature coefficient given on page 72 it will be at once evident that the total *increase* or *decrease* in the resistance of ab will be a_1R_1 ohms per 1° C., while that of bc will be a_2R_2 ohms per 1° C. Consequently the *total increase* or *decrease* in the resistance of the combination ac is

$$(a_1R_1 \pm a_2R_2) \text{ ohms per } 1^\circ \text{ C.},$$

where the $-^{ve}$ sign is used only in the case of the resistance R_2, decreasing with increase of temperature, *i.e.* when a_2 is $-^{ve}$.

Should a_1 also be $-^{ve}$, both products must then be added together, and the $-^{ve}$ sign prefixed to it merely to indicate a decrease of resistance. Now since the original total resistance $=R_1+R_2$ the combined temperature coefficient

$$a=\frac{a_1R_1 \pm a_2R_2}{R_1+R_2} \text{ ohm per ohm per } 1^\circ \text{ C.}$$

Further, it will be seen that the total resistance of ac, namely,

$R_1 + R_2$, will be perfectly constant at all temperatures providing $a_1R_1 = a_2R_2$, and this result has an important bearing on the winding of electrical measuring instruments to be dealt with later (*vide* p. 204).

Next take the case shown in Fig. 14 of the two resistances R_1 and R_2 in parallel between the points a and b.

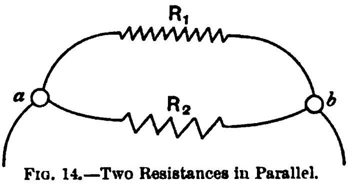


FIG. 14.—Two Resistances in Parallel.

The total increase or decrease of these resistances will, as before, be a_1R_1 and a_2R_2 ohms per 1° C. respectively. Hence, by the reasoning given on page 84, we have the original combined resistance

$$= \frac{R_1R_2}{R_1 + R_2}.$$

This for 1° C. difference in temperature becomes

$$\frac{(R_1 \pm a_1R_1)(R_2 \pm a_2R_2)}{(R_1 \pm a_1R_1) + (R_2 \pm a_2R_2)}.$$

Then by our definition of temperature coefficient on page 72 we have 'combined temperature coefficient'

$$a = \frac{\text{total increase or decrease of resistance per } 1^\circ \text{ C.}}{\text{original resistance}}$$

$$= \frac{\dfrac{(R_1 \pm a_1R_1)(R_2 \pm a_2R_2)}{(R_1 \pm a_1R_1) + (R_2 \pm a_2R_2)} - \dfrac{R_1R_2}{R_1 + R_2}}{\dfrac{R_1R_2}{R_1 + R_2}} \text{ ohm per ohm per } 1^\circ \text{ C.}$$

Reducing this to its lowest terms we finally have

$$a = \frac{(R_1 + R_2)(1 \pm a_1 \pm a_2 \pm a_1a_2)}{R_1 + R_2 \pm a_1R_1 \pm a_2R_2} - 1 \text{ ohm per ohm per } 1^\circ \text{ C.},$$

the $-^{ve}$ sign being employed only if R_1 or R_2 or both have negative temperature coefficients.

In the above manner the value of a can be found for any combination of resistances, providing the individual values of the coefficient are known.

Example 1.—The field magnet coils of a shunt-wound dynamo have a resistance of 140 ohms at 15° C., what will be their resistance at 25° C., the temperature coefficient of copper being = 0·00428 ?

From page 74 we have

$$R_2 = R_1\{1 + a(t_2 - t_1)\}.$$

Hence, substituting, we have

$$R_2 = 140\{1 + 0{\cdot}00428(25 - 15)\}$$
$$= 140 \times 1{\cdot}0428 = 145{\cdot}992 \text{ ohms.}$$

Therefore the total increase of resistance = 6·0 ohms very approximately.

Example 2.—If the shunt coils in the last question always have a P.D. of 200 volts at their terminals, what will be the value of the current taken by them at each temperature?

At 15° C. the current taken will be

$$A=\frac{E}{R}=\frac{200}{140}=1{\cdot}429 \text{ ampere.}$$

At 25° C. the current taken will be

$$A=\frac{E}{R}=\frac{200}{146}=1{\cdot}370 \text{ ampere.}$$

Example 3.—The working coil of a certain voltameter has a resistance of 140 ohms, and is wound with copper wire having a T.C. of 0·00428. It is placed in series with an extra resistance made of nickelin having a T.C. = 0·0003 and a resistance of 2860 ohms. Find the T.C. (a) of the combination.

From page 74 we have $\quad a=\dfrac{a_1R_1+a_2R_2}{R_1+R_2}.$

∴ substituting, we get

$$a=\frac{(0{\cdot}00428\times 140)+(0{\cdot}0003\times 2860)}{140+2860}$$

$$=\frac{0{\cdot}5992+0{\cdot}8580}{3000}=\frac{1{\cdot}4572}{3000}=0{\cdot}000485.$$

Example 4.—If the two resistances are in parallel instead of being in series, what will be the combined T.C.?

From page 75 we have

$$a=\frac{(R_1+R_2)(1+a_1+a_2+a_1a_2)}{R_1+R_2+a_1R_1+a_2R_2}-1.$$

∴ substituting, we have

$$a=\frac{(140+2860)(1+0{\cdot}00428+0{\cdot}0003+0{\cdot}000001284)}{140+2860+(140\times{\cdot}00428)+(2860\times{\cdot}0003)}-1$$

$$=\frac{3000\times 1{\cdot}004581284}{140+2860+0{\cdot}5992+0{\cdot}8580}-1=\frac{3013{\cdot}743852}{3001{\cdot}4572}-1$$

$$=1{\cdot}00409-1=\mathbf{0{\cdot}00409}.$$

The following table (V.) gives the specific electrical resistance (ρ) per inch cube and per cm. cube of the most important elements, together with the temperature coefficient (a). In the column headed relative resistance each substance has been expressed in terms of pure copper, which is taken arbitrarily as unity. This is a departure from the usual practice adopted in text-books, which invariably choose silver as the standpoint against which to compare other substances, owing to it having the smallest specific resistance. Copper, however, is

obviously the better standpoint of the two, since it is used to such an enormous extent in electrical engineering, and since very complete tables are almost always available which give every detail connected with copper that is likely to be required in practice. Table V. shows us that, of all the substances given, pure annealed silver has the least, and bismuth the greatest, resistance, for the same length and sectional area.

TABLE V

VOLUME SPECIFIC RESISTANCE (ρ) AND TEMPERATURE COEFFICIENTS (α) OF ELEMENTARY PURE, SOFT, AND ANNEALED SUBSTANCES IN ORDER OF INCREASING RESISTANCE.

Determined by Professors J. A. Fleming and J. Dewar.

Substance.	Composition.	ρ in Microhms[1] at 0° C. Per Cm. Cube.	Per Inch Cube.	Relative Resistance.	Mean α between 0° C. and 100° C.
Silver .	...	1·468	0·5781	0·9406	0·00400
Copper .	Very soft . . .	1·561	0·6146	1	0·00428
Silver[2] .	Hard drawn . . .	1·592	0·6269	1·020	
Copper[2] .	Hard drawn . . .	1·592	0·6269	1·020	
Gold . .	99·9 degrees of fineness.	2·197	0·8650	1·407	0·00377
Gold[2] .	Hard drawn . . .	2·234	0·8796	1·431	
Aluminium	Neuhausen, 99 % pure .	2·563	1·009	1·642	0·00423
Aluminium	Commercial, 97·5 % pure	2·665	1·049	1·707	0·00435
Magnesium	...	4·355	1·715	2·790	0·00381
Zinc . .	...	5·751	2·265	3·684	0·00406
Iron . .	Very pure . . .	9·065	3·569	5·806	0·00625
Iron . .	Less pure, containing 0·25 % Mn, 0·01 % S	10·512	4·138	6·733	0·00544
Iron[2] .	Telegraph wire . .	14·910	5·870	9·552	
Cadmium .	...	10·023	3·946	6·419	0·00419
Palladium .	...	10·219	4·024	6·546	0·00354
Platinum .	...	10·917	4·299	6·995	0·00367
Nickel .	...	12·323	4·851	7·893	0·00622
Tin . .	...	13·048	5·137	8·358	0·00440
Thallium .	...	17·633	6·940	11·29	0·00398
Lead . .	...	20·380	8·024	13·05	0·00411
Antimony[2]	Pressed	35·45	13·96	22·71	0·00389
Mercury .	...	94·07	37·03	60·26	0·000720
Bismuth[2] .	Pressed	131·18	51·65	84·95	0·00353

The resistance per cm. cube of any substance is 2·54 times the resistance per inch cube. Commercial metals show higher values of specific resistance than those given in the preceding table, owing to impurity. The increase is sometimes very considerable, and as an example *pure iron* and *iron telegraph wire* may be cited.

[1] The unit adopted is the Board of Trade or legal standard ohm (p. 45). Hence ρ is expressed in legal standard microhms.

[2] Not determined by Fleming and Dewar.

It will also be observed that the values given differ, in some cases considerably, from those noted in several other text-books, the reason being that at the present day increased facilities are available for obtaining purer elements than some years back, when the earlier results were deduced.

As an instance, some ten years ago all the copper employed in the manufacture of electric wires and cables was guaranteed to have a conducting power for electricity of as much as 96 and 97 per cent of that of pure copper. Nowadays it has 100 per cent of that of pure copper, due to the development of electrolytic methods of obtaining this metal.

The following table (VI.) gives the values of ρ and a for the most important alloys:—

[TABLE

TABLE VI

VOLUME SPECIFIC RESISTANCE (ρ) AND TEMPERATURE COEFFICIENT (α) OF ALLOYS IN ORDER OF INCREASING RESISTANCE.

Determined by Professors J. A. Fleming and J. Dewar.

The resistance per cm. cube of any substance is 2·54 times the resistance per inch cube.

Alloy.	Composition of Alloy.	ρ in Microhms[1] at 0° C.		Relative Resistance.[3]	Mean (α) between 0° C. and 100° C.
		Per Cm. Cube.	Per Inch Cube.		
Silverine	77 Cu + 17 Ni + 2 Fe + 2 Zn + 2 Co	2·064	0·8127	1·322	0·00285
Aluminium—Copper	94 Al + 6 Cu	2·904	1·144	1·861	0·00381
Titanium—Aluminium	...	3·887	1·531	2·490	0·00290
Aluminium—Silver	94 Al + 6 Ag	4·641	1·827	2·973	0·00238
Gold—Silver	90 % Au + 10 % Ag	6·280	2·473	4·024	0·00124
"	67 % Au + 33 % Ag	10·78	4·244	6·906	...
Brass[2]	Annealed, 70·2 Cu + 29·8 Zn	6·970	2·745	4·465	...
"	Hard drawn " "	8·226	3·239	5·270	...
"	Various kinds . . . Limits :—	6·4 to 8·3	2·52 to 3·268	4·1 to 5·32	0·001 to 0·002
Phosphor—Bronze[2]	Commercial wire, 80 % Pt + 20 % Ir	8·479	3·339	5·433	0·00064
"	Various kinds . . . Limits :—	5·0 to 10·0	1·97 to 3·94	3·2 to 6·4	...
Copper—Aluminium	97 % Cu + 3 % Al	8·847	3·483	5·667	0·000897
Aluminium—Bronze	...	12·300	4·843	7·879	0·0010
"[2]	Various kinds . . . Limits :—	11·7 to 13·4	4·61 to 5·28	7·5 to 8·6	0·0005 to 0·001
Copper—Nickel—Aluminium	87 Cu + 6·5 Ni + 6·5 Al	14·912	5·870	9·552	0·000645
Palladium—Silver	20 % Pd + 80 % Ag	14·964	5·891	9·585	...
Platinum—Rhodium	90 % Pt + 10 % Rh	21·142	8·324	13·54	0·00143
Nickel—Steel	Hadfields, containing 4·35 % Ni	29·452	11·60	18·87	0·00201
German Silver	Cu + Zn + Ni	29·982	11·80	19·21	0·000273
"[2]	60·16 Cu + 25·38 Zn + 14·02 Ni + 0·30 F	30·031	11·82	19·23	0·000361

[1] Board of Trade or legal standard microhms.

[2] Not determined by Fleming and Dewar.

TABLE VI.—*continued*

The resistance per cm. cube of any substance is 2·54 times the resistance per inch cube.

Alloy.	Composition of Alloy.	ρ in Microhms[1] at 0° C. Per Cm. Cube.	ρ in Microhms[1] at 0° C. Per Inch Cube.	Relative Resistance.[3]	Mean (α) between 0° C. and 100° C.
German Silver[2]	Various kinds . . . Limits :—	20 to 34	7·87 to 13·4	12·8 to 21·8	...
Platinum—Iridium	20 % Ir + 80 % Pt	30·896	12·16	19·79	0·000822
Platinum—Silver	66 % Ag + 33 % Pt	31·582	12·44	20·23	0·000243
Nickelin[2]	18·45 Ni + 61·64 Cu + 19·68 Zn + ·23 Fe + ·2 Co + ·19 Mn	33·22	13·08	21·28	0·000300
Platinoid	German Silver + 1 to 2 % Tungsten	41·731	16·43	26·73	0·000310
Constantan[2]	...	42·147	16·594	27·0	...
Manganin	84 Cu + 12 Mn + 4 Ni	46·678	18·38	29·90	− 0·00000
,, [2]	84 Cu + 12 Mn + 4 Ni	42·92	16·90	27·50	− 0·000025
Eureka[2]	Annealed	47·1	18·55	30·17	0·000005
,, [2]	Hard drawn	...	...	...	− 0·000011
Kulmitz (000)[2]	...	48·391	19·053	31·0	...
Rheostan[2]	53·29 Cu + 25·3 Ni + 16·9 Zn + 4·45 Fe + ·37 Mn	52·63	20·72	33·71	0·000411
Kruppin[2]	A steel alloy	57·757	22·740	37·0	...
Manganese—Steel	Hadfields, containing 12 % Mn	67·148	26·43	43·01	0·00127
Brunton's 'Beacon' Alloy[2]	...	74·928	29·5008	48·00	0·0007007
Resista	Hadfields, manganese steel alloy	75·5	29·724	48·36	...
Rheostene[2]	...	76·468	30·11	48·99	0·00110
Manganese-Copper[2]	70 % Cu + 30 % Mn	100·0	39·38	64·06	0·000040
Carbon[2]	From Ediswan glow lamps	39×10^2 to 41×10^2	1536 to 1614	2499 to 2626	− 0·00054
,,	Adamantine and arc light (Carré)	63×10^2 to 70×10^2	2480 to 2756	4035 to 4484	− 0·00050
,,	Retort . . . . . about	670×10^2	26380	42920	...

[1] Board of Trade or legal standard microhms. [2] Not determined by Fleming and Dewar.
[3] Expressed in terms of pure, very soft annealed copper (Table V.), having 1·561 microhms per cm. cube at 0° C.

In the second column of the preceding table only the chemical symbols (for brevity) have been used for the metals, the proportions of which, composing the alloys, are given. These chemical abbreviations will be found in Table III. page 43. Besides these, the following are used :—

Co for Cobalt.	Rh for Rhodium.
Ir ,, Iridium.	Mn ,, Manganese.
Pd ,, Palladium.	

The reason why it is convenient to compare the resistances of the alloys with that of pure copper is similar to that given on p. 76 in connection with the metals. For instance, suppose that we wish to know the resistance of 1000 yards of platinum silver of a certain gauge. All we have to do is to look up in the ordinary tables on copper conductors the resistance of 1000 yards of copper wire of the given gauge and temperature. Assuming this here to be 196·3 ohms, the 1000 yards of platinum silver will have a resistance (see Table VI.) of $196{\cdot}3 \times 20{\cdot}23 = 3971{\cdot}15$ ohms, or a resistance of 3·971 ohms per yard.

The results given in Table VI. show that, of all the substances, an alloy of copper and manganese has the greatest resistance and one of the smallest temperature coefficients. The non-metal carbon cannot be classed, in a sense, with the alloys, though it is true that the carbon given is not pure. The composition of the alloys, and with it the resistance, often varies considerably, for the admixture of an extremely small amount of foreign matter considerably increases the resistance of the metals.

Some interesting and extremely useful particulars and tables of figures relating to German silver, platinoid, galvanised iron, manganin, Krappin, Hadfield's 'Resister' alloy, and Brunton's 'Beacon' alloy will be found in a discussion on *metallic resistances* by E. K. Scott (*Electrical Review*, 43. pp. 71-72, 107-108, 187-188 ; 1898).

Krappin—made at Essen, Germany—is much used abroad, and it is claimed for this alloy that it will stand temperatures up to 600° C. without injury.

'Beacon' alloy has a specific gravity of 8·1, and has been known to have a specific resistance of 85·13 microhms per cm. cube at 20° C.

Specific Conductance—Conductivity.—The reader will at once see that as in the case of a supply of water or gas the conducting channel, *i.e.* the supply pipes, should offer as little obstruction to the free passage of the flow as possible. So in the supply of electricity, the conductor should offer the greatest facility for the passage of the current, *i.e.* should have the least possible resistance. The property

of any substance in virtue of which it allows of the passage of electricity through it is called its *conductance.* This property is obviously exactly the converse of resistance; or, if K is the conductance of a substance having R ohms resistance,

then $$K=\frac{1}{R} \text{ (mhos)},$$

and ∴ $$R=\frac{1}{K} \text{ (ohms)}.$$

In view of this relation between conductance and resistance, Lord Kelvin suggested that the unit of conductance should be called a *MHO* (p. 46), which is the word OHM written in the reverse way.

A mho therefore is the conductance of a column of pure mercury 106·3 cms. long, 1 square mm. in sectional area, at 0° C. (*vide* p. 45).

The above considerations lead us to the standard of reference for comparing the conductances of various substances. This is the conductance between opposite faces of a centimetre cube or inch cube of a substance in mhos, which is called the *specific conductance* or *conductivity.* It is the reciprocal of specific resistance or resistivity, consequently the reciprocal of the values of ρ given in Tables V. and VI. will be the specific conductances of the various substances in megamhos.

From the above remarks it follows that if L is the length of a conductor of cross section S and specific resistance ρ, its conductance

$$K=\frac{S}{L\rho} \text{ mhos.}$$

This relation is the converse of that given on page 69 for resistance.

In practice, the term conductance or conductivity is seldom used, it being customary to compare the carrying capacities of conductors of electricity by the smallness of their resistance and their cross-sectional area.

A comparison of the relative electric and heat conductivities of several of the metals is interesting, showing, as it does, that they arrange themselves in practically the same order, with one or two exceptions, in the two cases. In the following table the relative heat conductivities are approximately those determined by Wiedemann and Franz, while the relative electric conductivities are proportional to the reciprocals of the numbers in column 3, Table V.

TABLE VII

RELATIVE CONDUCTIVITIES FOR EQUAL LENGTH AND CROSS SECTION

Substance.	Electric.	Heat.
Silver	100	100
Copper	94	75
Gold	67	54
Zinc	25	20
Tin	11	15
Iron	16	11
Lead	7	8
Platinum	13	9
Palladium	14	6
Bismuth	1·1	1·9

If the electric and heat conductivities of the alloys and of insulating substances be compared, it is found that the electric conductivity decreases far more rapidly than the heat conductivity, particularly in the case of insulating substances.

Series and Parallel Circuits.—We may now consider the two main systems of arranging appliances to form an electric circuit, and the total resistance thereby introduced.

These are (1) *the series* and (2) *the parallel* systems respectively. All other arrangements of circuits, of which there are almost an unlimited number in practical work, are merely combinations of the above.

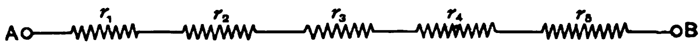


FIG. 15.—All in Series.

Resistances in Series.—Taking first the case of a number of appliances in simple series, *i.e.* all joined 'end on' to one another, as shown in Fig. 15, and represented by the wavy lines.

Now, since any current which may flow between A and B will encounter each resistance in turn, it is evident that *the total resistance of any number of separate appliances or conductors connected in series is equal to the sum of their separate resistances.*

Hence, if there are n appliances connected in series, the resistances of which are r_1, r_2, r_3, . . ., r_n, respectively, then the total resistance

$$R=r_1+r_2+r_3+. . .+r_n.$$

Or, by Ohm's Law (p. 66), as follows:—

Let V = the total potential difference between the extremities of a number of resistances in series;

C = current flowing through them;

v_1, v_2, v_3, . . ., v_n the P.D.'s at the terminals of r_1, r_2, r_3, . . ., r_n.

Then since $$V=v_1+v_2+v_3+\ldots+v_n,$$

$\therefore$ $$CR=Cr_1+Cr_2+Cr_3+\ldots+Cr_n,$$

i.e. $$R=r_1+r_2+r_3+\ldots+r_n.$$

In Fig. 15 $n=5$, whence the total resistance between the points A and B is

$$R=r_1+r_2+r_3+r_4+r_5.$$

The value of R is entirely independent of the order in which the different resistances are connected in circuit.

Resistances in Parallel.—Next consider the resistances r_1, r_2, r_3, . . ., r_n connected up in *parallel, branched*, or *divided circuit*, as it is variously termed, between the points A and B.

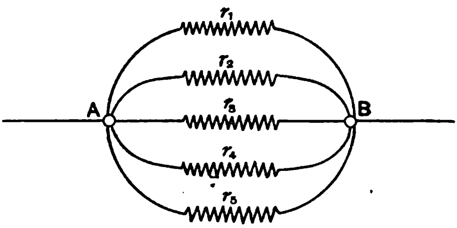


FIG. 16.—All in Parallel.

Fig. 16 indicates the arrangement. Now clearly it would be possible to substitute for the parallel combination between A and B a single resistance R which may be called the parallel, or combined, resistance of the combination, such that for the same P.D. (V) at its terminals the current (C) in the main or undivided circuit remained unaltered.

To find this, let V be the P.D. between A and B, and C_1, C_2, C_3, . . ., C_n the currents through r_1, r_2, r_3, . . ., r_n respectively.

Then the current in r_1 is

$$C_1=\frac{V}{r_1}$$

by Ohm's Law, and the current in r_2 is

$$C_2=\frac{V}{r_2},$$

and so on.

Similarly the current that would flow in R is

$$C=\frac{V}{R}.$$

But $$C=C_1+C_2+C_3+\ldots+C_n,$$

whence $$\frac{V}{R}=\frac{V}{r_1}+\frac{V}{r_2}+\frac{V}{r_3}+\ldots+\frac{V}{r_n},$$

and $\therefore$ $$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}+\ldots+\frac{1}{r_n}.$$

In other words, the reciprocal of the combined resistance is equal to the sum of the reciprocals of the resistances of the respective parallels; or,

again, the effective or combined conductance is equal to the sum of the separate conductances of the parallels.

In Fig. 16 $n=5$, and $\therefore$ $\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}+\frac{1}{r_4}+\frac{1}{r_5}$.
But if $n=2$,

then
$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2},$$

or
$$R=\frac{r_1r_2}{r_1+r_2}.$$

Again, it will be seen that if $r_1=r_2=r_3=r$, say,

then
$$R=\frac{r}{n},$$

where n = the number of equal resistances in parallel.

Fig. 17 shows

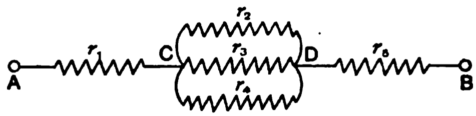


FIG. 17.—Partly Series and partly Parallel.

one combination of series and parallel circuits; and since by the preceding result the combined resistance between

$$\text{C and D}=\frac{1}{1/r_2+1/r_3+1/r_4},$$

$\therefore$ the total resistance between A and B is

$$R=r_1+\frac{1}{1/r_2+1/r_3+1/r_4}+r_5=r_1+\frac{r_2r_3r_4}{r_3r_4+r_2r_4+r_2r_3}+r_5.$$

Example 1.—An electric generator supplies current merely to one 100-volt electric glow lamp, having a resistance r_g of 300 ohms when glowing properly at 100 volts. What will be noticed when a voltmeter of 1000 ohms resistance (r_v) is connected to the lamp terminals in order to measure the P.D.?

The lamp alone will take a current

$$C=\frac{V}{r_g}=\frac{100}{300}=\tfrac{1}{3}\text{ ampere.}$$

If now the voltmeter be connected, we shall have this and the lamp in parallel, and hence their combined resistance will be given by

the relation
$$\frac{1}{R}=\frac{1}{r_g}+\frac{1}{r_v},$$

or
$$R=\frac{r_gr_v}{r_g+r_v}=\frac{300\times1000}{300+1000}=\frac{300000}{1300}=231\text{ ohms approximately.}$$

Thus the insertion of the voltmeter in parallel with the lamp has

reduced the resistance between the two points to which the lamp is connected from 300 to 231 ohms, or the whole circuit resistance by about 69 ohms; the result noticeable being the diminution of the brilliancy of the lamp, which is caused by the large alteration of circuit resistance.

Example 2.—If four electric glow lamps having respectively 400, 200, 100, and 50 ohms resistance be connected in parallel, what is their combined resistance?

We have
$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}+\frac{1}{r_4}$$
$$=\frac{1}{400}+\frac{1}{200}+\frac{1}{100}+\frac{1}{50}=\frac{1+2+4+8}{400}$$
$$=\frac{15}{400}.$$

∴ the combined resistance

$$R=\frac{400}{15}=\mathbf{26{\cdot}6\ ohms.}$$

Standard Resistances.—Having discussed the electrical properties of various well-known substances, we are now in a position to deal with another important subject, namely, *standard resistances* of known values. These are always required in the measurement of resistances, and often in that of E.M.F. and current. Now an ideal standard resistance should be one which does not alter in value from day to day and from year to year. We have, however, seen that all substances change their resistance with change of temperature; and further, it has recently been shown that many 'age,' especially after continued application of warmth, *i.e.* the substance seems to undergo some invisible change in itself which very gradually alters its resistance with time.

The *material* then to employ should be immune as much as possible from the latter property, should have a high *constant* specific resistance to obviate the necessity of having to employ great lengths for a given resistance, and, lastly, it should possess as small a temperature coefficient (p. 72) as can be accurately determined and allowed for.

In this latter case it is far better, for very accurate work, that the material used should have an appreciable temperature coefficient that is accurately known, than a very small but less accurately known one. At the same time it must not be so large as to necessitate correcting the resistance for ordinary changes of temperature which occur in a testing-room and for ordinary work. Double-silk-covered wire is used, the material largely employed in the past being German silver.

This has now been superseded to a very large extent by the alloys platinoid, eureka, and platinum silver, all of which have high specific resistances and low temperature coefficients.

The material should have as small a thermo E.M.F. with copper as possible. Nickel, copper, and especially constantan have a high thermo E.M.F. with copper and are not suitable for standard resistance coils of great accuracy. Manganin is better than constantan in this respect; but the latter resists oxidation better, and can be heated with impunity to 300° C.

The form taken by fixed *master standards* of resistance varies somewhat with the maker, that made by Mr. R. W. Paul, of London, being shown in Fig. 18. It consists of a coil of double-silk-covered platinum silver or manganin wire (usually the former), non-inductively wound in the form of a flat double spiral. This is enclosed in, but insulated (with mica) from, a thin flat discoidal metal box. This is formed of two recessed discs bolted together, the joint between them being of V form, filled in with special water-tight packing. The two stout copper rods, held together rigidly by the ebonite block, pass through the ebonite top of the vertical metal tube which is carried by the flat box as a foot. These rods are so fixed that the soldered joints of the coil to their ends cannot be strained by roughly handling the standard; the two free ends being intended to dip into mercury-cups, and so make connection to the circuit. The wire of the coil is carefully aged, and adjusted extremely accurately to 1 part in 10,000 at the temperature stamped on the standard and as measured by a standard thermometer immersed with the standard in a water or paraffin-oil bath. The form of all master standard resistances should be such that they quickly take the temperature of the bath, for the whole difficulty lies in accurately determining the temperature of the coil. An error may also creep in due to conduction of heat through the stout copper rods from the outside.

FIG. 13.—1-Ohm Standard Resistance.

The *adjustable* form which known standards of resistance most frequently take is shown in general principle by Fig. 19. A mahogany

box B is closed by an ebonite lid E, to the under side of which are fixed four ebonite or boxwood reels or bobbins A, or as many more as may be desired.

To the top of EE are securely fixed five (or more) brass blocks b_1 to b_5, these being at least one (usually two) more in number than the number of bobbins A. Each block is separated from the next by a narrow air-gap G, and the adjacent ends of the blocks are bored so as to form a small conical hole tapering downwards at each of the four gaps shown.

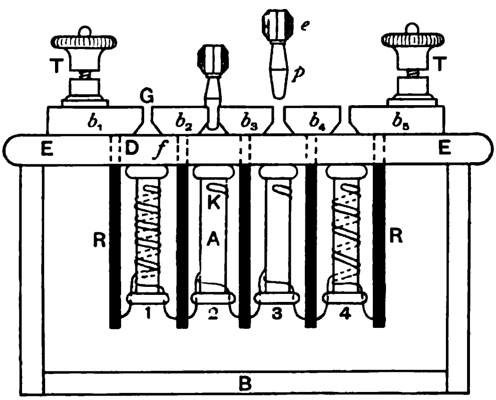


FIG. 19.—Construction of Standard Resistance-Box.

Into these holes fit brass plugs p having exactly the same taper, so as to fit accurately, each plug being provided with an ebonite handle e of some convenient shape, into which the shank of p is screwed and pinned.

To the brass blocks at the extreme ends of the series are fixed the terminals T, T, the best form of these for this purpose being that shown in Fig. 19. Screwed into each block and projecting through the ebonite lid E is a stout brass pin or rod R, though sometimes two are screwed side by side into each block. To the ends of R are soldered the ends of the wire resistance coils, which are wound on the bobbins A and carefully adjusted to have an exact, even number of ohms resistance: say 1, 2, 3, and 4 ohms, as marked. It will now be seen that a resistance coil has its ends electrically connected to two adjacent blocks so that the insertion of a plug in a hole, such as that between blocks b_2 and b_3, will join the ends of the 2-ohm coil through a very small resistance (equal to that of the plug and its contacts). In other words, the coil is said to be short-circuited, and its resistance entirely cut out.

The total resistance between the terminals T, T, as indicated, is 1 + 3 + 4, or 8 ohms; for the current, entering at the left-hand terminal say, flows through coil 1 *via* b_2, b_3, through coils 3 and 4, and out.

Hence the terminal resistance in all cases is equal to the sum of the numbers opposite unplugged holes.

The arrangement depicted in Fig. 19 would only have a total resistance of 10 ohms, with any intermediate value between 1 and 10,

by 1 ohm at a time. By having more coils any resistance from 1 to, say, 11,110 ohms, with 1-ohm variations at a time, can be obtained.

The usual values of the coils fitted in a box to total the above resistance are:—

1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1000, 2000, 3000, 4000; or
1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1000, 2000, 2000, 5000.

But there are other values, the first set being that used in Post Office work, and the most convenient for summing up. Thus 16 coils will produce 11,110 different resistances, varying by 1 ohm at a time.

In the better resistance-boxes the blocks are undercut as shown at D*f*, which is partly to facilitate removal of dust which tends to accumulate on the ebonite lid between the blocks, but principally to prevent current leaking across the film of dust or clean ebonite surface instead of it all going through the coil when this has a high resistance. Obviously the coil and such a film are in parallel, and therefore the resistance between these two adjacent blocks would be less than that of the coil (p. 84), and errors would result.

An 'infinity' plug is usually provided, *i.e.* two adjacent blocks are not connected at all inside the box, so that the circuit is broken on removing the plug.

The method of fixing the bobbins A varies with different makers. That shown in Fig. 19 is one method, a slight variation of it being to provide each coil with a pair of pins R, so that the soldered connections are independent of one another, and replacing a coil would in no way interfere with the adjustment of that on either side. This is an advantage, but two pins have to be screwed into each block. Another way is to slip the bobbins over the pins themselves, which therefore act as supports for the coils and connections to blocks as well.

The resistance wire (double-silk-covered) is not wound on the bobbins in a continuous helix, for then each bobbin would become an electro-magnet on the passage of a current through it and would act magnetically on any indicating instrument in the vicinity, so making observation very difficult, if not erratic. To overcome this difficulty the wire is doubly wound, as indicated in Fig. 19, so as to be non-inductive; and this is done by carefully jointing together the two free ends of the resistance wire on two reels, insulating the joint and then winding the requisite amount of double wire on to the bobbin, such as A, Fig. 19, off the two reels together.

Thus the current enters one end of such a coil, flows round it in one direction to the loop or joint K, Fig. 19, and then round in the opposite direction. Consequently the magnetic effect due to one half

of the coil neutralises that due to the other half, and no external magnetic influence is produced by the coil. The bobbin thus wound is adjusted carefully to the required resistance in the manner to be indicated later. It is then thoroughly dried or baked in a suitable drying oven to get rid of any moisture in the insulation, and finally soaked in a bath of melted paraffin wax, which excludes all moisture when the coil is cold.

Fig. 20 shows the general appearance of a standard parallel-plug resistance-box made by Messrs. Nalder Brothers and Co., of London. To economise space the coils and brass blocks are arranged in two rows as seen, and the plug on the extreme right is usually the 'infinity' plug.

FIG. 20.—Adjustable Standard Resistance-Box.

Space will not permit of a description here of the different forms of plug-tops employed with such resistance-boxes, some of which, particularly that known as the 'dial' form, enable the resistance both to be varied and totalled up more rapidly. The author, moreover, must be pardoned for digressing from usual custom in not describing, with one exception, some of the many uses which these resistance-boxes can be put to in the measurement of current, pressure, resistance, and power; suffice it here to say that such will be found fully described in the author's works entitled *Practical Electrical Testing in Physics and Electrical Engineering*, and *Electrical Engineering Testing.*

The Wheatstone Bridge.—The exception referred to above is a specially arranged resistance-box called a Wheatstone bridge; and the arrangement of this, together with the principle involved in the use of it, is of such extreme importance to the electrical engineer that a description is indispensable.

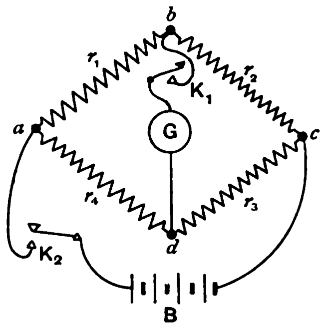


FIG. 21.—Principle of the Wheatstone Bridge.

The principle, which was developed or brought into practical use by the late Sir Charles Wheatstone, and is evolved from an application of Ohm's Law (p. 65) to divided circuits (p. 84), is as follows:—

Suppose that a source of electric current B be connected through a device K_2, for making and breaking circuit, to two points *a* and *c*,

between which is a divided or parallel circuit *abc* and *adc*. It will be obvious (p. 48) that, since the two branches join one another at the points *a* and *c*, for every point in the branch *abc* there will be some point in the other branch *adc* having exactly the same potential. If now *b* and *d* are any two such points of equipotential, and they are connected together electrically through a current-detecting instrument or galvanometer G, as it is often called, and also through a key K_1 similar to K_2, then no current will pass through G, *i.e.* from *b* to *d*, on closing K_1, as the non-deflection of G will prove, owing to there being *no difference* of potential (p. 49).

Thus the current flowing in *ab* will be the same as that in *bc*, and the current flowing in *ad* will be the same as that in *dc*, when G indicates no current in the cross path *bd*.

Now let r_1, r_2, r_3, r_4 be the respective resistances of the paths *ab*, *bc*, *cd*, *da*; and let C_1, C_2 be the currents through *abc* and *adc* respectively. Also let v_1, v_2, and v_3 be the potentials of the points *a*, *b*, and *c* respectively, when v_2 will also be that of the point *d*.

Then we have by Ohm's Law :—

$$C_1 = \frac{v_1 - v_2}{r_1} = \frac{v_2 - v_3}{r_2},$$

and

$$C_2 = \frac{v_1 - v_2}{r_4} = \frac{v_2 - v_3}{r_3},$$

or by division

$$\frac{r_4}{r_1} = \frac{r_3}{r_2} \text{ or } \frac{r_1}{r_2} = \frac{r_4}{r_3};$$

whence

$$\mathbf{r_1 r_3 = r_2 r_4}.$$

This may be termed the *law of the Wheatstone bridge*; and the bridge itself, we see, is an arrangement of six conductors joined three together at four points.

The above law, it will be observed, still holds even if B and G are interchanged in position. Consequently balance—*i.e.* the adjustment of the arms r_1, r_2, r_3, r_4, as they are called, so that G does not indicate any current—is unaffected by interchanging B and G. We may now indicate the way in which a resistance can be measured by the Wheatstone bridge.

Suppose r_3 to be the unknown resistance to be measured, and that standard known resistances (Fig. 20) are inserted to compose the remaining three arms r_1, r_2, and r_4 respectively. Then to make a measurement, suitable known resistances are inserted in r_1, r_2, and r_4, the key K_2 now pressed, and r_1, r_2, and r_4 adjusted so that on pressing K_1 in addition to K_2 G does not deflect.

Then we have

$$r_3 = \frac{r_4}{r_1} \cdot r_2.$$

The battery key K_2 must always be pressed before the galvanometer key K_1, so as to allow the currents in the arms of the bridge to attain their steady strengths before the galvanometer key K_1 is closed. If a highly inductive circuit is being measured, this may take several seconds, due to the phenomenon of inductance (*vide* p. 194).

It must here be noted that if r_2 is in ohms, r_3 will also be in ohms, no matter what units r_1 and r_4 are in, so long as they are the same units.

This fact makes it possible to employ what is called the 'metre form' of Wheatstone bridge, in which *adc* (Fig. 21) is a stretched wire 1 metre long, of uniform cross section, and r_2 a resistance-box as before. *d* is now a moving contact by which a point such as *d*

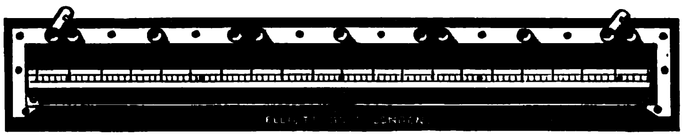


FIG. 22.—Metre Bridge.

can be found by trial, having the same potential as *b*. Thus the unknown resistance $r_1 = \frac{r_4}{r_3} \cdot r_2$, and $\frac{r_4}{r_3}$ is now a ratio of the two lengths of the wire either side of the sliding contact *d*.

A common form of metre bridge is shown in Fig. 22. It consists of a base board a little longer than 1 metre, and some 20 cms. wide, roughly, to which is screwed, in this instance, five separate thick copper strips. The end strips are bent round at right angles, and between the extremities is stretched a platinum-iridium wire 1 metre long, indicated in the figure by the white line. Capable of sliding over this wire throughout its whole length is a spring tapping key provided with a terminal. Contact can therefore be made with any point of the wire by pressing the key, the position being noted on a metre scale as shown. The three intermediate copper strips are provided with terminals at their extremities and middle points, as also are the end strips. Thus four gaps in the line of strips are formed, enabling resistances to be connected across them. For ordinary work, however, only two gaps, one either side of the centre strip, are needed, in which are connected the unknown and standard resistances respectively, the two remaining gaps being bridged by massive copper strips seen in Fig. 22, of negligibly small resistance. From the previous remarks, then, the position of the sliding key will be *d*, and the centre terminal of the middle strip *b*, while *a* and *c* will be any corresponding pair of terminals on the remaining strips.

The reader is, however, referred to the special books mentioned on page 90 which deal with this all-important subject of measurement, where all the principal methods of, and precautions to be used in, measuring current, pressure, resistance, and power are fully described and explained.

The formation of a Wheatstone bridge by separate resistance-boxes in the manner above mentioned would, in the majority of cases met with in practical work, be inconvenient. To obviate this, three of the arms and the two keys K_1 and K_2 are arranged compactly in a somewhat similar form to that met with in an ordinary resistance-box. This is shown diagrammatically in Fig. 23, and in the corresponding general view, Fig. 24.

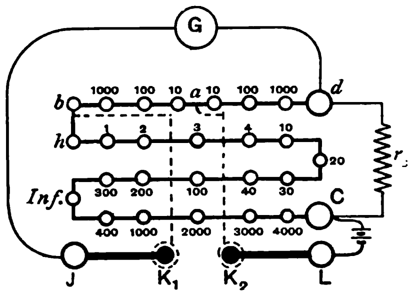


FIG. 23.—Diagram of Post Office Wheatstone Bridge.

Referring to the former, which is lettered so as to exactly correspond with Fig. 21, it will be seen that the arms *ab* and *ad*, called the proportional arms, each consist of three resistance coils of 10, 100, and 1000 ohms respectively. This is in order to obtain always a very simple and convenient ratio of r_4 to r_1 (Fig. 21).


FIG. 24.—General View of Post Office Bridge.

The remaining three rows, comprising 16 coils and one 'infinity' plug, form the adjustable or balancing arm of the bridge. The unknown resistance is r_3, to be measured as before.

The dotted lines from *a* and *b* (Fig. 23) are permanent connections inside the box to the under contact studs of the spring lever-tapping keys K_1 and K_2, which can be clearly seen in Figs. 23 and 24.

A double form of terminal is fixed at C and *d*, so that the two

connecting wires which go to each of these points need not be clamped under one and the same nut, thereby risking a bad connection. Single terminals are provided at *b*, *h*, J, and L, though in the normal use of the bridge *b* and *h* are connected by a stout copper plate. Since the 16 coils in the adjustable arm total 11,110 ohms, it will be seen that this bridge, which is known commonly as the Post Office pattern, will measure resistances between $\frac{10}{1110} \times 1$ or $\frac{1}{111}$th ohm, and $\frac{1110}{10} \times 11,110$ or 1,233,210 ohms.

The accurate range of measurement, however, for reasons which will not be discussed here, lies between about $\frac{1}{10}$th of an ohm and 200,000 ohms.

It may be well to point out that the kind of *plug*-top adjustment already described is always used with standard resistances of the highest accuracy.

For ordinary commercial or less accurate work some makers in this country and abroad employ sliding or rubbing switch contacts, which they state have a conductivity and reliability equal to that of well-fitted plugs.

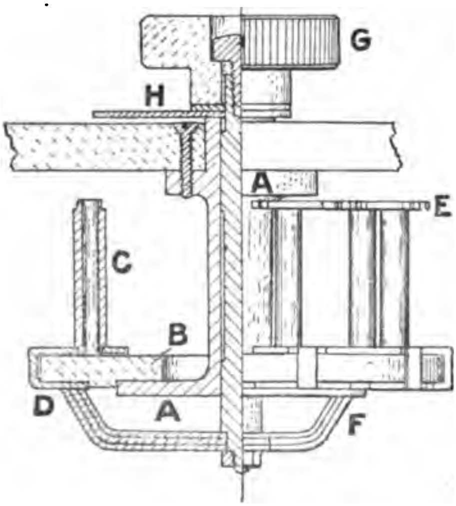


FIG. 25.—Sliding-Contact Resistance Box (Half-Side Sectional Elevation).

The improved form of dial resistance, with enclosed switch, recently introduced by Mr. R. W. Paul, of London, is shown in half-side sectional elevation (Fig. 25) and in half plan of the upper and lower sides of the contact-block disc (Fig. 26). The coils are wound on brass bobbins E provided with lugs to which the ends of the coil are soldered, and with switch contact-plates or blocks D formed in one piece. One end of a substantial laminated switch-brush F makes a rubbing contact on the plates D, which are undercut where attached to the ebonite disc B so as to give good insulation and free circulation of air through the hollow core C. The other end of the brush makes a good rubbing contact on a central flange-plate A which supports the bobbins E, these latter being insulated by the ebonite disc B. It will thus be seen that the phosphor-bronze switch-spindle carries

no current, as the current passes between the plates D and A directly through F. The spindle can be turned by an ebonite knob G, its position, and therefore that of F on D, being indicated by an attached pointer H. A screw adjustment, seen inside G, is provided for taking up the wear between DA and F in course of use.

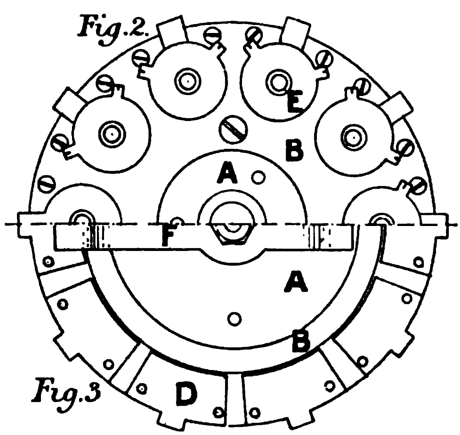


FIG. 26.—Sliding-Contact Resistance-Box (Half-Plan Sectional Elevation).

Every 'dial resistance' is complete in itself and contains 10 coils non-inductively wound with silk-covered wire of low temperature coefficient (about 0·000008 per 1° C.), which is so small as to render any correction for ordinary atmospheric changes of temperature in this country unnecessary. Only G and H project through the ebonite lid on which the values of the coils are legibly engraved. The coils are well baked, and coated with shellac to render them proof against the effects of hot or damp climates. The Universal Shunt, illustrated in Fig. 33, is constructed on this principle. Dial and parallel resistances with open switch-contacts are also made by different makers, that by Messrs. R. Frank and Co., of Hanover, being shown in Fig. 27.

Fault-Localising Bridge.—Before going further we may give one important application (out of many) of the Wheatstone bridge principle for the determination of the position or distance of a *fault*, *i.e.* of a bad leakage or breakdown, from the generating station in an electric main or cable.

The instrument in which the principle is applied has recently been put on the market by Messrs. Nalder Brothers and Company, of London, and is known as the portable Direct-Reading Fault-Localising Bridge.

A general view of the instrument is shown in Fig. 28, and a diagrammatic sketch of the arrangement and connections in Fig. 29.

It consists of a somewhat massive guide-bar, terminating at one end in a terminal L and at the other in a key K. A uniform stretched wire runs from the terminal F, along a scale, on one side of the guide-bar, and back on the other side. A portable jockey or key P can make contact with any point of the stretched wire, while a sliding jockey S can be set at any position on its guide-bar. A

battery has one of its poles connected to a fixed terminal B, and the other to the earth or lead sheathing of the cable under test.

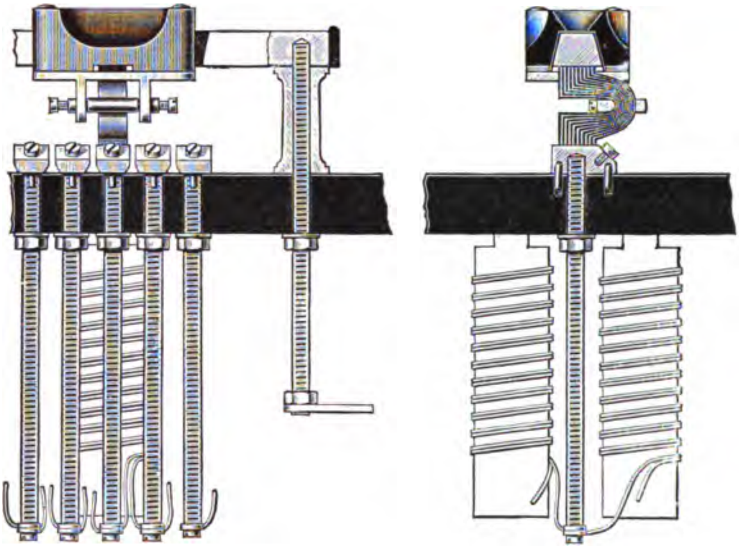


FIG. 27.—Sliding-Contact Resistance-Box, by Messrs. R. Frank and Co.

The faulty cable is connected to terminals F and L, and the galvanometer to those marked GG.

To make a test, set S to the length of the cable loop, and find the position of P at which no deflection on the galvanometer is obtained, by pressing down this jockey-key P at different positions on the wire and then tapping the galvanometer key K.

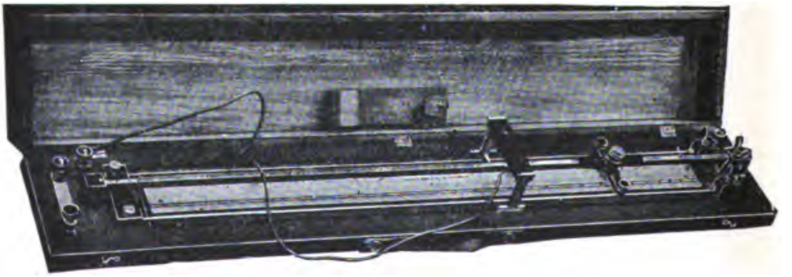


FIG. 28.—Direct-Reading Fault-Localising Bridge.

The reading of the position of P on the scale when balance is thus obtained is the distance of the fault from the terminal F. The instrument, therefore, gives the distance of the fault from the station by a simple balancing test, and the test is independent of the resistance of the cables (which is often not known with accuracy). In this way a

dead earth, short circuit, or fault of appreciable resistance can be easily found.

Shunts.—Resistances of known and practically constant values have another important application in practical work, which we will now consider. Suppose that it is desired to measure a certain current

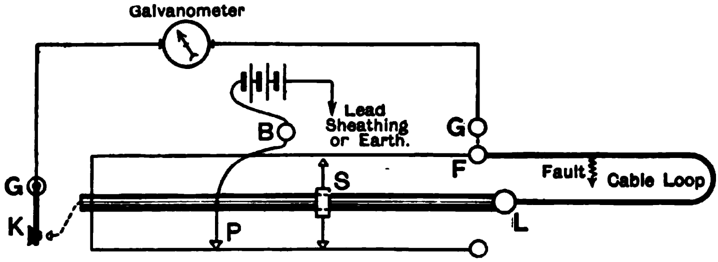


FIG. 29.—Principle and Connections of Fault-Localising Bridge.

of electricity by means of some indicating instrument, or *galvanometer*, as it is often termed, such as that described on page 206; also that this instrument is too sensitive to measure so strong a current when placed in series with the circuit, *i.e.* its indications are always off the scale, and cannot therefore be read.

Now the principle of parallel circuits considered on page 84 will suggest that a second circuit should be formed between the terminals of the instrument, and therefore in parallel with it, to act as a 'bypath' for the excess current over and above what the instrument will measure.

Such a bypath is usually termed a '*shunt*,' and it is so commonly employed in practice that it is important to consider what resistance the shunt must have, relatively to that of the instrument, in order that a given fraction of the total current may pass through the latter.

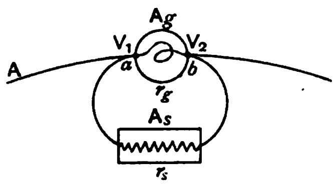


FIG. 30.—Theory of Shunts—Symbolical Sketch of Principle.

Referring to the arrangement depicted symbolically in Fig. 30, let A, A_g, and A_s be the currents in the main circuit, instrument, and shunt respectively, and r_g, r_s the resistances of galvanometer and shunt, and V_1, V_2 the potentials of the two points a and b (the terminals of the instrument), between which it and the shunt are in parallel. Then the P.D. at the terminals of instrument or shunt $= V_1 - V_2$; and from Ohm's Law—

$$A_g = \frac{V_1 - V_2}{r_g},$$

and $$A_s = \frac{V_1 - V_2}{r_s},$$

$\therefore$ $$\frac{A_s}{A_g} = \frac{r_g}{r_s}.$$

But $$\frac{A_s}{A_g} + 1 = \frac{r_g}{r_s} + 1,$$

or $$\frac{A_s + A_g}{A_g} = \frac{r_g + r_s}{r_s},$$

and obviously $$A = A_s + A_g.$$

Whence $$\frac{A}{A_g} = \frac{r_g + r_s}{r_s},$$

and $\therefore$ $$A_g = \frac{r_s}{r_g + r_s} . A,$$

or $$A = \frac{r_g + r_s}{r_s} . A_g.$$

From this result we see that the galvanometer current A_g must be multiplied by the quantity $\frac{r_g + r_s}{r_s}$ (called the *multiplying power of the shunt*) in order to obtain the value of the total current A. The combined resistance R of shunt and instrument will (from p. 85) be

$$R = \frac{r_s . r_g}{r_s + r_g}.$$

Now suppose it is known that the main current is roughly about five times stronger than a given instrument can measure. We then desire that A_g shall be $\frac{1}{5}$ of A, and therefore from the above we have

$$\frac{r_s}{r_s + r_g} = \frac{A_g}{A} = \frac{1}{5},$$

or $$r_s = \frac{1}{4} r_g,$$

i.e. the shunt resistance must be $\frac{1}{4}$ of that of the instrument.

Obviously any standard known adjustable resistance-box can be employed as a shunt to an instrument if the resistance of the latter is known.

Special forms of shunt-boxes (of which there are several) are, however, supplied with the more delicate instruments, and which usually have three shunts, for use only with the particular instrument. The shunts are usually arranged so that only the convenient fractions $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$ of the total current passes through the instrument, the remainder through the shunt, depending on which is in use.

To obtain this, the last equation shows us that the shunt resistances must be $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of that of the instrument respectively.

One very common form of shunt-box is shown in Fig. 31, and the diagram of connections in Fig. 32. As seen, it consists of a brass containing-case having an ebonite top and base.

To the top are fixed the five separate segmental blocks A, B, C, D, E of a brass ring, which surround a central brass block F.

Two double terminals, T_1, T_2, are fixed to blocks A and B, and block B is permanently connected to F. By means of the one or sometimes two plugs that are provided, C, D, or E can be connected to F on inserting the plug, and A can be connected to B.

FIG. 31.—General View of Shunt-Box.

The three resistance coils r_1, r_2, and r_3, having respectively $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ the resistance of the galvanometer, are connected between the common block A and C, D, E respectively. These resistances should be wound with the same material as that used in the galvanometer coils, so that they vary in exact proportion with that of the galvanometer for any changes of temperature. The shunt-box is connected to the two galvanometer terminals by short wires W, W.

If a plug be inserted between A and B, the terminals T_1, T_2, and therefore the galvanometer, are short-circuited; but if the plug be inserted instead in one or other of the remaining three holes, say between D and F, then the $\frac{1}{99}$th shunt is connected across T_1 and T_2, and therefore shunts $\frac{99}{100}$ of the main current past the galvanometer.

The shunt coils r_1, r_2, and r_3 are wound to the requisite resistance with the same material as used in the coils of the instrument. This obviates any errors that would otherwise be introduced in the shunting power due to the different temperature coefficients of the two branches (*vide* p. 75).

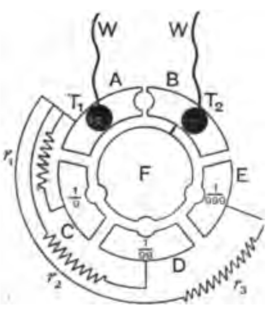


FIG. 32.—Diagram of Connections of Shunt-Box.

Universal Shunts.—The chief disadvantage of the preceding form of shunt-box is that it can be used *only* with the galvanometer for which it was made.

With a view to obviating this difficulty, Professor Ayrton and Mr. Mather[1] devised the principle known as their '*universal shunt.*' This device has the great advantage that it is available for use with any galvanometer, and also gives a *constant* damping effect, thus reading correctly when used with ballistic galvanometers (p. 209).

[1] *Press Proc. I.E.E. and Electrician*, vol. xxxii. p. 627.

The principle is shown diagrammatically in Fig. 33, which indicates the connections of an improved form introduced by Mr. R. W. Paul and illustrated in Fig. 34.

The galvanometer is joined to the two terminals G_1, G_2, which are connected to the extremities of a series of seven accurately proportioned and adjusted resistances. The sum of all these = 10,000 ohms, and each bears an exact ratio to the total, such as 1000, 300, 100, etc., which are termed the *shunting powers*. The main circuit is joined to the terminals T_1, T_2, which in turn are connected in the box as shown.

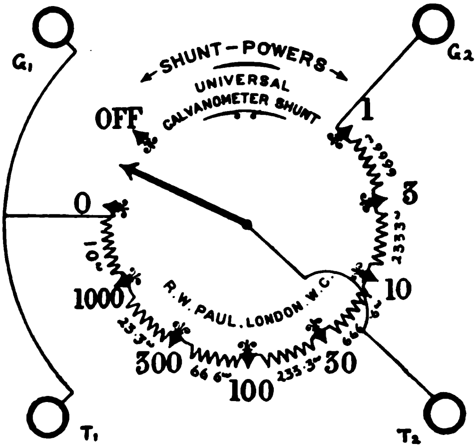


FIG. 33.—Principle and Connections of Universal Shunt.

If, then, the movable contact arm is on stud marked 100 say, it means that only $\frac{10+23\cdot3+66\cdot6}{10000}$ or $\frac{1}{100}$th of the total current is passing through the galvanometer, and so on with other studs.

The instrument may be used as a *ratio box* for enabling a low-reading voltmeter (p. 230) to measure higher voltages. In this case the pressure to be measured is connected to G_1, G_2, and the voltmeter to T_1, T_2, when it will be seen that the voltmeter measures known fractions of the total P.D. Change of temperature does not affect the multiplying power, and greater accuracy is obtained than with the previous form of shunt-box. If the resistance of the shunt is not more than twenty-one times that of the galvanometer, the resistance of the whole circuit is varied less than when using an ordinary shunt-box.

FIG. 34.—General View of Universal Shunt.

Other forms of shunt-boxes, constant current and otherwise, will be found described in the laboratory text-book, *Practical Electrical Testing*, by the author.

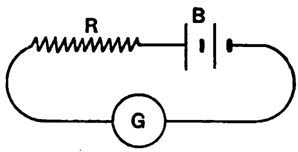


FIG. 35.—Diagram of Simple Circuit.

The employment of a shunt with certain instruments may, however, introduce errors into the measurement, and in other cases may not produce the desired and looked-for effect.

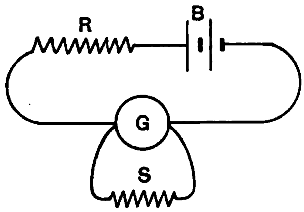


FIG. 36.—Diagram of Simple Circuit and Shunt Galvanometer.

As an example of the latter case, suppose that we have a simple series circuit (Fig. 35), consisting of a resistance R = 27 ohms, source of E.M.F. (E) of 2 volts, and having an internal resistance B of 4 ohms, and a galvanometer G of 999 ohms resistance, the connecting wires being of negligibly small resistance. Then by Ohm's Law the current (A) flowing in the circuit is

$$A = \frac{\text{total E.M.F.}}{\text{total resistance}} = \frac{E}{R+B+G} \text{ amperes.}$$

$$\therefore \quad A = \frac{2}{27+4+999} = \frac{2}{1030} = 0{\cdot}00194 \text{ ampere.}$$

Now consider the same circuit, but with the galvanometer shunted (Fig. 36) with a shunt S of $\frac{1}{9}$th.

The main circuit current, *i.e.* the current from the battery, is

$$A = \frac{E}{R + B + \frac{SG}{S+G}} = \frac{2}{27+4+99{\cdot}9} = \frac{2}{130{\cdot}9} = 0{\cdot}0153.$$

Hence shunting the galvanometer has increased the main current from 0·00194 to 0·0153, which, as we see, is due to the diminution of the galvanometer resistance from G to $\frac{SG}{S+G}$.

But the fraction of this total current which now flows through G is only $\frac{S}{S+G}$ of the main current. Hence the galvanometer current

$$= \frac{S}{S+G} \times \frac{E}{R + B + \frac{SG}{S+G}}$$

$$= \frac{999 \times \frac{1}{9}}{(999 \times \frac{1}{9}) + 999} \times 0{\cdot}0153 = \frac{111}{1110} \times 0{\cdot}0153 = 0{\cdot}00153 \text{ ampere ;}$$

and this is nearly as large as the previous total current, namely, 0·00194 ampere.

Thus it is important to remember that under certain conditions the diminution of main circuit resistance due to shunting an instrument

may so increase the total current that the fraction $\frac{S}{S+G}$ of the new total current is nearly as large as the original current, and hence the reading of the instrument is not diminished nearly as much as required.

If R had been large, say 3000 or 4000 ohms, it would be found that shunting would practically not have altered the main current, so that the galvanometer current would actually have been reduced in the desired proportion, viz. $\frac{S}{S+G}$.

Standard Low Resistances.—Up to the present no special mention has been made of resistances having values below 1 ohm, and which are usually termed *low* resistances. We may confine ourselves here to that type which is adjusted to an accurately known value, and which remains *constant* under the conditions of use imposed on it, thus constituting a known *standard* of low resistance.

FIG. 37.—Standard 0·1-Ohm Low Resistance for 10 Amperes.

Such standards are usually constructed to carry large currents, and are mainly used in the measurement of other low resistances of unknown value and in that of current by potentiometer methods (*vide* p. 226).

The material used in their construction is usually *manganin* or a *nickel-copper alloy*, which is thoroughly 'annealed' and 'aged' beforehand, the cross-sectional area of metal and the radiating surface being so proportioned that the error in resistance due to rise of temperature (which is usually restricted to 30° C.) caused by the passage of the maximum specified current does not exceed 0·025 %.

For currents up to about 5 amperes, standard resistances are usually made in the form of open spirals of round wire, and are either exposed to the air or, when it is desirable to know their temperature, immersed in an oil-bath provided with a thermometer. For larger currents they are made of one or more broad or narrow metal strips connected in parallel between massive metal end-blocks to which the main circuit cable is attached. The length of the resistance wire or strip is in all cases made a trifle longer than that actually required to give the desired resistance, and small *potential terminals* are connected at intermediate points on it, between which the *exact* resistance exists.

Fig. 37 is a 0·1-ohm standard resistance for a maximum current of 10 amperes, made by Messrs. Elliott Brothers, of London. The

resistance is contained in an outer case having holes in the sides, and its ends are clamped to the lower ends of the two massive studs. The

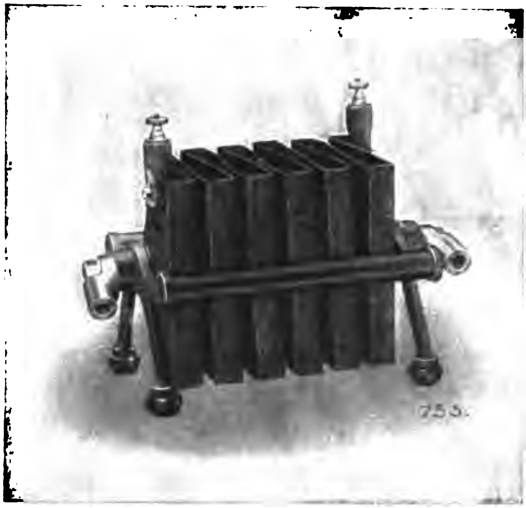


FIG. 38.—Standard 50-Ampere Low Resistance.

main circuit cable or wire can be attached to sweating thimbles, which are clamped under the hexagonal nuts on the studs. The smaller

FIG. 39.—Standard 2000-Ampere Low Resistance.

potential terminals between which the exact resistance exists are also shown on the cover of the containing case, which is filled with oil.

Fig. 38 shows a standard 50-ampere resistance made by Messrs. Crompton and Company, of Chelmsford. It consists of a broad strip, bent into a zigzag shape to economise space, and mounted on a light frame. The extreme ends carry cable thimbles, and the two small potential terminals are on the top. This and all similarly constructed standards for use in the air are fixed on edge so as to facilitate cooling by convection, etc.

A 2000-ampere Crompton standard is shown in Fig. 39, and

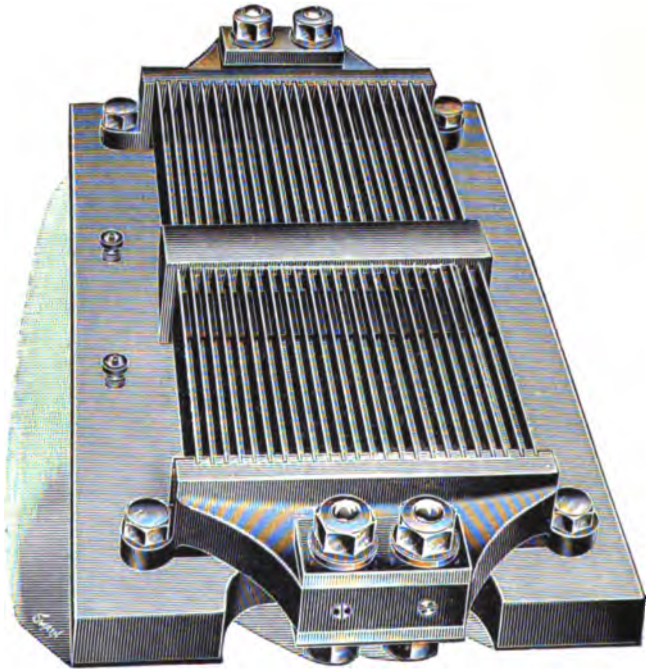


FIG. 40.—Standard 0·0002-Ohm Low Resistance for 1500 Amperes.

consists of eight strips in parallel between the two thimbles, the two potential terminals being carried on a terminal board at the top as seen.

A 1500-ampere 0·0002-ohm standard resistance made by Messrs. Elliott Brothers is illustrated in Fig. 40, and consists of twenty-four strips in parallel side by side between two massive metal end-blocks. Each of these blocks is provided with two bolts for clamping the ends of the main circuit to.

The potential terminals are shown at the left-hand side of the base, and the cross-piece at the centre of the strips is for the purpose of keeping them rigid and equally spaced apart.

A similar standard to this (by the same maker) for 3000 amperes has a resistance of 0·0001 ohm, and would therefore have a fall of potential at its terminals of $3000 \times 0{\cdot}0001$, or 0·3 volt at the maximum current.

Insulation.—From what has been said in the earlier pages of this book the reader will at once see that to utilise electricity it is not only necessary to provide some kind of path for it to act along, usually termed a conducting path, or briefly a conductor, but also to provide the means, usually called *insulation*, for restricting or preventing it acting along any other path simultaneously. Any substance which prevents the passage of electricity, either along or through it, in all but minute quantity is termed an *insulator* or *isolator*. The very best insulator known has, however, some conductivity, in the same way that the very best conductor has some resistance.

The introduction of the higher pressures so commonly employed nowadays has almost simultaneously taken place with the production of better and cheaper insulating material, without which it would be dangerous, if not impossible, to work with them.

Probably next to that of the actual production of electricity, no subject has received such widespread attention as that of insulation. Its vast importance to the electrical engineer may be judged from the fact that both the production and utilisation of electricity depend on sufficiency of insulation in one way or another.

Properties of Insulating Materials.—In order that any particular insulating material may withstand the various uses to which it may be put at the present day, it should possess the following properties, namely, that it should be (1) a good insulator, *i.e.* should have a high insulation resistance, which ought not to diminish much for any rise of temperature that the material may have to undergo; (2) waterproof and non-hygroscopic, *i.e.* it should not absorb moisture of any kind; (3) fireproof; (4) tough; (5) flexible and not brittle, so as to permit bending and twisting; (6) have a dielectric strength or rigidity sufficient to prevent rupture from sparking at all ordinary temperatures; (7) easily obtainable in any shape or form, and easy to work. A substance possessing all these properties would be an ideal insulator, but probably no such material exists, one or more of the properties being usually absent.

Temperature in all cases seriously diminishes the insulating properties of a substance, and in abnormal amount may alter the chemical constitution of the material. On the other hand, the insulation resistance increases up to a certain point with the time during which it is subject to electrical pressure, or, shortly, to the time of electrification. With most insulators there is a greater change of resistance,

due to change of temperature, after long electrification than after a short time of electrification. The insulation resistance of many substances, and almost invariably of electrical cable insulation, is in this country taken after one minute's electrification, and after twenty-four hours' immersion in water at about 15° C. In this way a comparison between the various kinds of insulation can be made.

The specific resistance at a specified temperature is given for various important substances in Table VIII. The values, however, can only be taken as merely approximate, owing to even a slight variation in the composition altering the resistances considerably, and also to the effects of electrification and age. For instance, the resistance of gutta-percha increases very much with age if kept under water. Mechanically flexible insulation, giving tolerably high resistance, can be obtained by treating fibrous material with linseed or other oil, drying, and finally thoroughly baking it. The same fibrous material treated with resin, shellac, etc., has different properties, being more brittle and liable to crack, while having a higher insulation resistance.

Mica, though expensive in the better qualities, is used in very large quantities for physical and electrical engineering appliances. It is an excellent insulator, does not deteriorate with high temperature, and has a high dielectric strength for resisting rupture due to sparking. Mr. T. O. Moloney has found, however, that the dielectric strength of mica is reduced by fully one-half its normal value by lightly coating its surface with paraffin oil. Mica can be split into uniform sheets less than 1 mil ($= \frac{1}{1000}$ inch) in thickness, but is brittle, and cracks when bent too much. It is also practically non-hygroscopic. Many large firms make their own sheets of insulating material by cementing their irregularly shaped pieces of scrap mica together by means of thin but sticky insulating varnish made from shellac, resin, etc. Sheets carefully built up in this way with lap joints have a dielectric strength and insulation resistance nearly as high as a continuous mica sheet, while being much more flexible and amenable to bending round corners.

[TABLE

TABLE VIII

APPROXIMATE VALUES OF SPECIFIC RESISTANCE AND OTHER PHYSICAL PROPERTIES OF IMPORTANT INSULATORS (ARRANGED IN ALPHABETICAL ORDER)

Substance.	Specific Resistance in Megohms per		Temperature in °C.
	Cm. Cube.	Inch Cube.	
Benzine (liquid)	14×10^6	$5 \cdot 22 \times 10^6$	
Bitumen cable (Callendar's)	450×10^6	177×10^6	15
Colza oil	$0 \cdot 1 \times 10^6$ to $1 \cdot 5 \times 10^6$	$0 \cdot 039 \times 10^6$ to $0 \cdot 59 \times 10^6$	
Ebonite	$28{,}000 \times 10^6$	$11{,}030 \times 10^6$	46
Glass (flint)	$20{,}000 \times 10^6$	7874×10^6	20
,, (ordinary)	91×10^6	$35 \cdot 9 \times 10^6$	20
Gutta-percha	25×10^6 to 450×10^6	$0 \cdot 99 \times 10^6$ to 177×10^6	24
,,	7000×10^6	2756×10^6	
Hooper's compound	$15{,}000 \times 10^6$	5905×10^6	24
Ice	2240	882	$-12 \cdot 4$
,,	284	112	$-0 \cdot 2$
India-rubber (Hooper's vulc.)	$15{,}000 \times 10^6$	5905×10^6	24
,, (crude)	$10{,}901 \times 10^6$	4292×10^6	$14 \cdot 9$
,, (ozokerited)	6601×10^6	2600×10^6	$15 \cdot 2$
,, (vulcanised)	3812×10^6	1501×10^6	$15 \cdot 1$
,, (Siemen's special)	$41{,}148 \times 10^6$	$16{,}200 \times 10^6$	15
,, (refined)	$16{,}202 \times 10^6$	6380×10^6	15
Mica	84×10^6	33×10^6	20
Micanite	2490×10^6	981×10^6	
,, (cloth)	310×10^6	122×10^6	
,, (paper)	1240×10^6	481×10^6	30
,, (plate)	2067×10^6	814×10^6	30
,, (,,)	1727×10^6	680×10^6	100
Oil asbestos	$0 \cdot 85 \times 10^6$	$0 \cdot 315 \times 10^6$	
Olive oil	1×10^6	$0 \cdot 394 \times 10^6$	
Ozokerite	$44{,}000 \times 10^6$	$17{,}347 \times 10^6$	
Paper (parchment)	$0 \cdot 03 \times 10^6$	$0 \cdot 0112 \times 10^6$	20
,, (ordinary)	$0 \cdot 0485 \times 10^6$	$0 \cdot 019 \times 10^6$	20
,, and resin oil	3000×10^6	1181×10^6	15
Paraffin	24×10^3 to 34×10^3	9449 to 13,396	46
Paraffin wax	$34{,}000 \times 10^6$	$13{,}385 \times 10^6$	46
Resin oil	320×10^6	126×10^6	18
Shellac	9000×10^6 to 2286×10^6	3543×10^6 to 9000×10^6	28
Vulcanised fibre (black)	68×10^6	$28 \cdot 6 \times 10^6$	
,, (red)	10×10^6	$3 \cdot 9 \times 10^6$	
,, (white)	14×10^6	$5 \cdot 5 \times 10^6$	
Wood (ordinary)	572×10^6	225×10^6	
,, (paraffined)	3690×10^6	1453×10^6	
,, (tarred)	1670×10^6	658×10^6	
,, (walnut)	53×10^6	$20 \cdot 8 \times 10^6$	

Note.—The resistance per cm. cube of any substance is 2·54 times the resistance per inch cube.

Vulcanised fibre consists of paper treated chemically and afterwards compressed and dried. It is very hard, and can be worked easily with machine and other tools. It, however, chars when heated in air to the higher temperatures and becomes brittle. Vulcanised fibre is rather hygroscopic, and when dried is liable to warp.

A list of special insulating materials recently introduced is given in Table IX., many of these being of foreign origin.

TABLE IX

SPECIAL ARTIFICIAL AND OTHER IMPORTANT INSULATING MATERIALS IN COMMON USE (ARRANGED ALPHABETICALLY)

Ambroin	Lithin	Sapho
Armacell	Litholite	Silex
Armalac	Manson tape	Slate
Asbestos	Megomit	Stabilit
Bitumen	Okonite	Steatite
Celluloid	Ozite	Talc
Dialite	Pitch	Uralite
Diatrine	Porcelain	Velvril
Eburin	Press-spahn	Volcnite
Enamellac	Psychiloid	Vulcabeston
Fuller Board	Resin oil	Vulcanite
Insulite	Rhynox fibre	Wicksite
Isolit	Rubellite	Woodite

Numerical data in connection with the physical properties of most of the substances enumerated in the above table are scarce, but we may give some particulars of a few of them.

Silex has recently been introduced into America, and consists of pulverised rock. It is used in the form of powder, being packed round bare conductors when laid in troughs or piping. It is non-hygroscopic, non-inflammable, durable, and cheap in first cost.

Vulcabeston is a mixture of rubber and asbestos, which undergoes a special process. It is a good insulator, is unaffected by high temperatures, is non-hygroscopic, and is very hard and strong, but has a resistance to rupture less than that of mica.

Diatrine is a good insulating material, resembling rubber in appearance, and having considerable dielectric strength. It is non-hygroscopic, flexible, and possesses considerable mechanical strength, and is used by Messrs. Glover & Co. for insulating electric light cables.

Ambroin is mostly composed of mica, resin, and amianth, which are well ground and mixed together and then treated chemically, being finally heated under pressure. Its specific gravity ranges from 1·4 to 1·8, and it can be moulded into any shape, and gives a smooth surface. It is unaffected by light, only slightly hygroscopic, resists acids, and is not much affected by heat or boiling water. Ambroin is stronger than ebonite mechanically, and offers greater resistance to compression.

Velvril consists of nitrated castor or linseed oil mixed into a thoroughly homogeneous mass with nitrocellulose. It is intended as

a substitute for india-rubber, and is more stable than either this or gutta-percha. The hardness of velvril can be varied by the composition. It is inflammable, burning slowly but non-explosively.

A new insulating compound has recently been introduced, consisting of granite chips, which are calcined and mixed with kaolin, powdered felspar, and sufficient water to make a plastic mixture. This is then moulded into any shape or form, heated to nearly 1700° C., and finally glazed. It is practically non-hygroscopic, has great tensile and compressive strength, and a high insulation.

Ebonite and *celluloid* begin to soften in water at 160° F., and burn at 350° F.

Okonite stands temperature extremes better and with higher insulation resistance than any rubber insulation.

Leakage.—On page 105 it was stated that even the very best insulator, by reason of its possessing some slight electrical conductivity, allows some, though it may be a very small quantity of electricity to pass it, which is called *leakage.*

Now this leakage takes place in two ways :—

1. Through the mass or whole cross section of the insulation.

2. Along the film of moisture and dirt on the outside surface of the insulation.

Though leakage always takes place in the above two ways simultaneously, we often find one or other of them the main source; for example, 1 almost entirely results in the case of leakage from a lengthy electric insulated cable, whereas it is only 2 that is met with principally in leakage from the overhead trolley wire to earth in an electric tramway system. Here the outside of each of the strain insulators is covered with a film of moisture and dirt, which forms a conducting path far exceeding in conducting power that through the insulator itself. The reader will not therefore have much difficulty in seeing that *dirt* and *moisture* are the two main enemies of insulation, of which the latter is the principal one. The best insulation results with any insulator will be obtained, so far as dirt is concerned, when its surface is highly polished, for then dirt will have much greater difficulty in adhering to it.

It is unfortunate that many excellent insulators are hygroscopic, *i.e.* absorb moisture from the air. The best results will, however, be obtained from those which are hygroscopic, by polishing the surface and then varnishing it with a non-hygroscopic, highly insulating varnish.

For example, glass is an excellent insulator when clean and dry, but it absorbs moisture very soon. If coated with shellac varnish it becomes a fairly good insulator, so long as the varnish remains clean.

The shellac varnish should, however, be made with care, and consist of clean lumps of what is termed 'button' lac dissolved in pure alcohol. Under usual conditions of use, a *clean* and *dry* glass surface is a higher insulator than when it is coated with shellac.

Paraffin wax is almost non-hygroscopic, and is frequently used to coat the end of an electrical insulated cable to prevent leakage from the copper core over the end of the insulating covering to the outside and thence to earth. In such cases, which usually occur in testing work, the clean paraffin wax, melted in a receptacle placed in a hot-water bath, should be painted over a freshly bared portion of the insulation at the end.

Laws of Leakage of Electricity.—Now it is obvious that the longer the path of leakage the greater will be the resistance opposing it, both at the surface and in the mass of the insulator itself; also the greater the surface, and therefore the greater the cross section, the less will be the resistance opposing leakage. The opposite, both in the case of length and surface, must also be true, so that we are able to formulate the following rules:—

Let l and s be the length and surface width respectively of any insulator. Then the surface or insulation resistance will be

$$\propto \frac{l}{s}.$$

If the insulator be cylindrical, s will be $\propto \pi d$, where d is the diameter of the circular cross section. Whence the surface resistance will be

$$\propto \frac{l}{\pi d}.$$

The resistance opposing leakage through the cross section of the material itself will be given by the rule on page 69, and

$$= \frac{l\rho}{\mathrm{A}} \text{ ohms,}$$

where A = the cross-sectional area, and ρ = the specific resistance of the material as given in Table VIII. page 107.

If the section is circular, $\mathrm{A} = \frac{\pi d^2}{4}$,

and the resistance becomes $\frac{4l\rho}{\pi d^2}$ ohms.

l, ρ, and d must of course be in similar units.

With fairly good insulators, surface leakage almost entirely eclipses in magnitude the leakage through mass, and is the main thing to guard against, so that l is the factor to make as large as possible and

s that to reduce as much as is consistent with obtaining sufficient rigidity in the insulator.

Now in order that l, the effective length of the path along which leakage may take place in any insulating pillar or support, may be large without the support being tall and consequently weak, recourse may be had to the form shown in Fig. 41. This consists, as seen, in deeply grooving or corrugating the pillar from one end to the other, the depth of the grooves depending on the outside diameter of the pillar. The advantages of this construction are:—(1) The value of l, the effective length of surface from end to end, can easily be made at least twice that of a plain cylindrical rod of the same length; (2) the support can be made stouter, and therefore stronger, with the same insulation resistance for equal length; (3) in handling the support the recesses will escape being soiled by contact with the hand, though the outer ridges will be dirtied by touching, consequently a continuous film of dirt will not be formed from end to end, and the insulation of the support will in a great measure be maintained. Supports of this kind are always fixed by metal thread-screws s, s screwed into the ends. The hole required for the thread inside it should on no account be drilled right through the support, but only just so far as is necessary for obtaining a sufficient number of threads to enable the screw to get a firm hold of the support. A hole right through the centre will in a great measure nullify the good insulating effect due to corrugating.

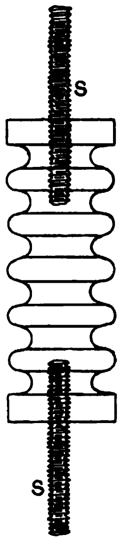


FIG. 41.—Corrugated Insulating Pillar.

Insulators for supporting Electrical Conductors.—We may now consider briefly the main characteristics pertaining to insulators when used for *supporting* electrical conductors, as distinguished from the insulating covering of the conductors themselves. Supporting insulators are used in the open air and also under cover or indoors; but as the conditions of use in open air are so vastly more severe than those met with under cover, any insulator capable of coping with the former will all the more easily cope with the latter. We may therefore confine our attention more particularly to those intended for use in the open air for supporting bare conductors. Much attention has of late years been given to this subject by engineers with a view to enabling electrical power at high pressures to be transmitted over long distances with very little leakage. The trouble in the past was the somewhat wide variation of insulation resistance with the changes of weather, but this trouble has practically been overcome now by

properly designed insulators, which are lighter and have better electrical properties and can be carried, even by good conducting supports, with equally good results. The attributes of an ideal insulator are that it should be :—(1) Hard but not brittle ; (2) made of a non-hygroscopic substance ; (3) made of an anti-acid-proof material ; (4) very smooth, to prevent accumulation of dust and dirt, and be easily cleansed by rain ; (5) very strong, to enable it to withstand crushing due to the dead-weight of the wire when still and also fracture through lateral strain when the line is swaying in a wind, or abrasion by the line ; (6) to have maximum length of total surface opposing leakage combined with minimum periphery of transverse section, or, in other words, with minimum cross section of material ; (7) constructed as to prevent insects from settling in any recesses and so reducing the resistance ; (8) so constructed that a flaw in one part cannot ruin the insulating properties of the whole insulator.

Material employed for Insulators.—Various materials have been used in the manufacture of insulators, such as glass, ebonite, white and brown porcelain, white and brown stoneware, while for electric railways and tramways a special compound is employed which is homogeneous and moulded under pressure from a plastic condition. It is well suited for withstanding rough use, being very tough, strong, durable, and hard but not brittle. Further, it is practically non-hygroscopic and unaffected by climatic changes.

Hitherto the main objections to the use of glass have been its hygroscopic nature, due to the alkali in it having great affinity for moisture, and the liability which it has to 'fly' or split. Further, since the angle of contact between water and glass is zero, a drop of water spreads almost indefinitely, thus creating a moist conducting film which directly promotes leakage. On the other hand, glass in certain qualities is one of the best insulators, so far as leakage through its mass goes, and within the last three or four years insulators have been introduced made of a coarse kind of glass. The composition of this glass is a trade secret, but alkaline constituents have been avoided, so that no film of water condenses on the surface. Further, the difficulty of casting caused by this is overcome, and by a special annealing process the liability of the insulator to 'fly' has been got over. Results of tests on these show that both in dry and wet weather they are between two and ten times better in insulation than similar porcelain samples, also that no brush discharge, at high voltage, occurred with glass as it did with porcelain, and that higher pressures were resisted better with the former than with the latter. In some parts of Western America where the air is exceptionally

pure and dry, power is transmitted at 60,000 volts through wires insulated only by ordinary telegraph insulators made of *glass*. We may therefore conclude that the new form of glass insulator has probably a great future before it for insulating high-pressure wires and even telegraph wires, seeing that with these surface leakage, especially in damp weather, is the main source of trouble.

Ebonite is objectionable for aerial insulators, because it is costly and its surface becomes acid. Owing also to rain adhering to it, the surface soon becomes covered with a dirty and spongy conducting film.

Porcelain with a non-alkaline glaze makes an extremely good insulator. White and brown glazed porcelain, and stoneware or earthenware, are by far the two most widely used materials for line insulators. Porcelain, as now made, is the better and most widely used of the two, owing to its insulating qualities being much better than those of earthenware, and to them being to a great extent independent of the outer glaze. The material, however, varies considerably, and with it the insulating properties; and the material under the glaze may even be porous and spongy, so that if this glaze cracks, moisture is rapidly absorbed and the insulator ruined. Brown earthenware made from clay, being very hard and durable, is a good material for insulators, and is cheap. Although it is incapable of taking as good a glaze as porcelain, the glaze is not so liable to crack. Porcelain, however, has the advantage that its specific resistance is higher than that of earthenware.

The best insulators are *hand-turned*, and *not moulded*, as many of the commoner ones are; and it should be remembered that, as surface conduction is the main trouble in all insulators, the point of first importance is the condition of the surface. The higher the glaze the better, for then the moisture drops off and the surface is more thoroughly cleansed by rain. Now, in order to combine the two very important attributes (5) and (6) mentioned on page 112, the most commonly used insulators are made in the form of a simple cup, or as many as two and three cups, one inside the other. There are, however, many different forms in use, and space will only permit of the description of some of those used extensively. Of the two distinct classes of insulators made, namely (1) those used with oil and (2) those in which no oil is employed, the latter are the simplest in construction. These insulators are mostly of the double-cup form, the single- and triple-cup forms not having been adopted to any great extent so far in practice. Multiple-cup insulators of this class are made either in one piece or built up of cups made separately

and afterwards cemented together. The latter arrangement is to be preferred, because a flaw in one cup does not utterly ruin the whole insulator as it might if this were made in one piece.

Fig. 42 shows a common form of Post Office Telegraph insulator of the double-cup or shed type. The galvanised wrought-iron bolt (not shown) which carries it has a jagged end, similar to that of the bolt shown in Fig. 46 at K, for the purpose of being gripped by the current. This end is cemented into the hole H, which is provided with two annular grooves G, G for the purpose of keying-in the cement. As seen (Fig. 42), the two cups B and C are made in one piece, the body of which has a circular groove AA to which the wire to be supported and insulated is fixed. The lip of the outer cup B, at least, should be shaped as shown, so that drops of water hanging from the rim are merely blown a little way up the bevelled edge inside without being broken and thus wetting the inside of the insulator. The path of surface leakage from the wire at A to the supporting bolt is in the direction of the arrows, and is of considerable length, as it should preferably be. Moreover, the inner cup C, being shallower than B, is mostly dry, and therefore insulates very highly. This form of insulator, often called a '*terminal insulator*,' is nearly always made in white glazed porcelain, and measures about $4\frac{1}{4}''$ high × $3\frac{1}{2}''$ outside diameter.

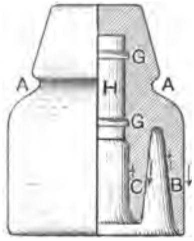


FIG. 42.—Double-Cup Non-fluid Insulator.

Fig. 43 illustrates a triple-shed glazed porcelain insulator for high-pressure electrical transmission of energy. As seen, there are three distinct cups made in one piece, and the interior S is screwed for the reception of a screw-threaded bolt. Such a '*screw-bolt*' insulator, as it is called, whether of a single- or multiple-cup form, is all but universally adopted on account of the facility with which renewals can be made. The form in Fig. 43 is often called a '*top-groove*' insulator, on account of a groove T being provided at the top, usually to take a cable $\frac{3}{4}''$ or $1''$ diameter. It also has a side groove *aa*, and the path of surface leakage is as shown by the arrows, being extra long, and consequently giving extra high insulation. An insulator somewhat similar to this, and of the triple-shed form, when tested with an alternating pressure having a constant rate of reversal of 50 periods per second, and ranging from 5000 to 50,000 volts, has

FIG. 43.—Triple-Cup Non-fluid Insulator.

been shown by Mr. R. M. Friese [1] to have an insulation resistance of about 1000 megohms and an electro-static capacity of 0·000026 microfarads.

A somewhat similar insulator to this last one, made of highly vitreous porcelain, and intended for high pressures, is supplied by Messrs. Bullers, Ltd. It is of the triple-shed type, but the lower portion of the innermost cup extends below the lowest edge of the middle one, and that of the latter below the lowest edge of the outermost cup. It is stated to be extremely strong and tough and suited to all climates, while its insulation resistance is said to not depend on the outer glaze.

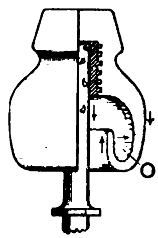


FIG. 44.—Simple Oil Insulator with Bolt.

A simple but very effective '*oil*' insulator is shown in Fig. 44, and is of the single-cup type. It will be seen that the lip of the cup bends up inwards, forming an annular channel in which a non-evaporative highly insulating oil O is placed. The insulator is often made with a *top groove*, though only one at the side is shown in the figure. Either a screwed or cemented jagged bolt is used, and the illustration indicates the latter. Any leakage of current from groove to bolt is shown by the arrows, and has to take place across the clean surface of the highly insulating oil O. The insulation resistance of this class of insulator is consequently high, and it is therefore well suited for high-pressure lines.

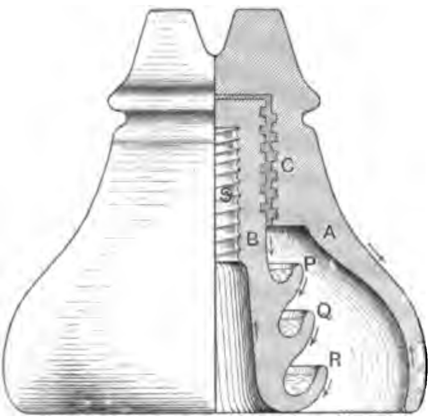


FIG. 45.—Oil Insulator, triple trough.

Fig. 45 illustrates the form of Phillips's oil or fluid insulator supplied by Messrs. Johnson and Phillips to the Oerlikon Company for the transmission of power at high pressure between Kriegstetten and Solothurn. The line, 8 kilometres long, consists of bare copper conductors supported on these insulators. At a pressure of 2000 volts the leakage was practically nothing, thus showing the perfect insulating qualities of this form of insulator. As will be seen, it is made in two distinct parts, A and B, which are cemented together as indicated at C. The outer cup A is practically the cover, and is

[1] *Elektrotechn. Zeitschr.* 24. pp. 1028-30, Dec. 1903.

provided with both top and side grooves. The inner part B is provided with a screw-thread S to enable the insulator to be screwed on to a bolt, and on the outer periphery of B are formed three annular channels or cups, P, Q, and R, in which oil is placed. Leakage between conductor and bolt takes place in the direction of the arrows, but has now to cross three distinct oil surfaces in P, Q, and R.

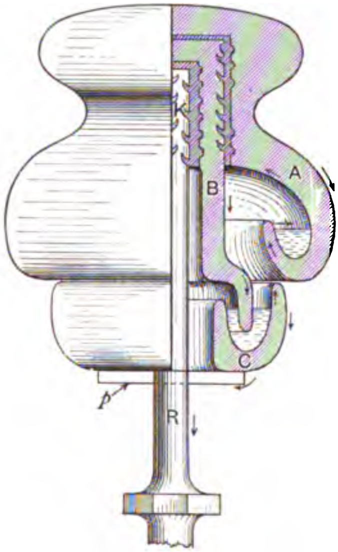


FIG. 46.—Oil Insulator, double trough.

Another form of Phillips's fluid insulator, in three pieces, with sliding cup, is shown in Fig. 46. The outer cup A has a side groove and a section similar to that shown in the figure. Into this is cemented the cup B, the lip of which dips into a third or sliding cup C, which like A contains oil. A bolt R has its jagged end K cemented into the inner cup B, and supports the whole insulator. The sliding cup C is lowered to be filled with oil, and then slid up R, being supported in position as shown by a pin (p) which passes through the side of the bolt. The direction of leakage is as shown by the arrows.

It is sometimes necessary to provide an insulator with protection against malicious injury by attaching it to a metal cap. Fig. 47 shows such an arrangement, or a hooded insulator with what is called a $\frac{1}{2}''$ pigtail or hook. The hood now supports the insulator, and is bolted to the post.

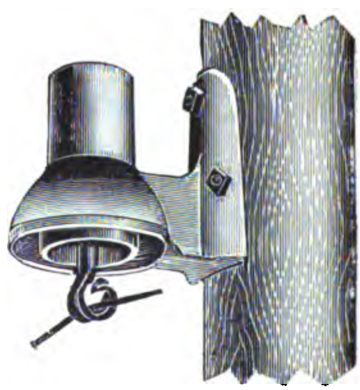


FIG. 47.—Metal Cap Insulator.

When heavy conductors have to be supported, a different form of insulator for standing the heavy strain is often used. This is commonly known as the shackle insulator, and may be of the fluid type or otherwise. The fluid or oil type of such an insulator is shown in Fig. 48 in side and sectional elevation, and is of the double-cup form. As actually depicted, we have what is known as the *double*-shackle form, consisting of two porcelain

insulators I, I, each being clamped between the ends of a pair of galvanised wrought-iron straps S, S by the stout iron bolts shown. The other ends of the straps S are drilled with holes to take a stout

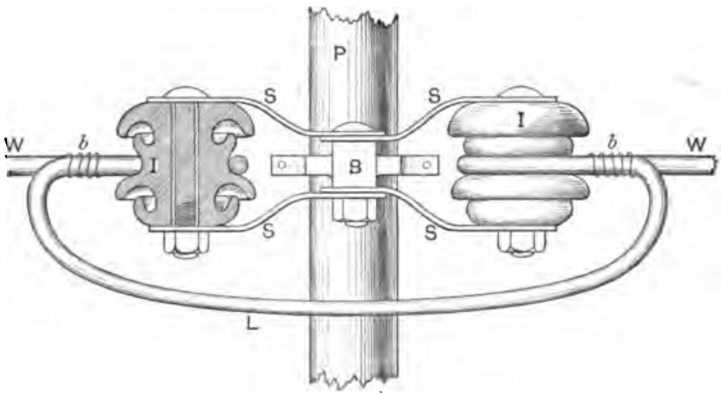


FIG. 48.—Shackle Insulator on Post.

bolt, which passes through the hole in the projecting lug B of a clamp. This clamp is in two halves, and when these are bolted together the post P is firmly gripped. The cable W is bent once round each insulator and bound by small wire, as at b, b, a loop L being formed. Each shackle insulator I is free to swivel on the bolt at B, and hence such an arrangement is a convenient one to employ at corners, and it will be seen that the bolts through each insulator practically take all the strain.

FIG. 49.—Cable Suspender (Raw Hide.)

Bare aerial mains or electrical conductors are bound to the grooves of insulators such as those shown in Figs. 42 to 48, or run as indicated in Fig. 47. In the case of insulated cables, however, this method would damage the insulation on the cable at the insulators, due to friction introduced by the cable swaying to and fro in the wind. In such a case the insulated copper cable is suspended by a special form of suspender from either a solid or stranded steel cable carried by the insulators adopted. One form such a suspender takes is shown in Fig. 49. Here the copper cable is supported

in what may be termed a 'running noose' made out of a leather thong. A split double eye of steel carries the thong and hangs on the steel suspension wire. Thus the copper cable can swing in the wind without any part of its insulation being chafed.

QUESTIONS ON CHAPTER IV

[*Supplement all Answers with Sketches when possible.*]

1. What current will an E.M.F. of 100 volts send through an electric circuit of 5 ohms resistance?

2. A circuit has a resistance of 2 ohms, and the current flowing through it is 10 amperes. Find the E.M.F.

3. If the circuit in the last question had a back E.M.F. of 50 volts, what must the value of the impressed E.M.F. be?

4. What will be the resistance of a circuit which carries 100 amperes when the P.D. at its terminals is 100 volts?

5. State the laws of resistance for any electrical circuit, and show how they can be used for finding its resistance.

6. A conductor, composed of a material having a temperature coefficient $=0{\cdot}389\,\%$ per degree Centigrade, has a resistance of 1000 ohms at 15° C. What will be its resistance at 30° C.?

7. Find the rise of temperature necessary to cause a resistance of 5000 ohms to rise to 5200 ohms.

8. An electrical circuit is constructed of two different materials in series, one having a resistance of 50 ohms with a temperature coefficient (T.C.) $=0{\cdot}00389$, the other of 3000 ohms with a T.C. $=0{\cdot}00044$. What is the combined T.C. of the whole circuit?

9. Find the combined T.C. of the two materials mentioned in Question 8, when placed in parallel.

10. What is the combined resistance of three circuits of 3, 6, and 9 ohms respectively in parallel?

11. Find the combined resistance of a circuit composed of 3 ohms in series with a parallel combination of 6 and 9 ohms.

12. What must be the resistance of a shunt so that $\frac{9}{10}$ths of the total current may pass through a galvanometer of 1000 ohms resistance?

13. What fractions of the total current pass through a galvanometer and shunt, respectively, when their resistances are 5 and 20 ohms?

14. Find the multiplying power of the shunt in Question 13.

15. If the current through a galvanometer is to be $\frac{1}{100}$th of the total current, what must be the ratio of the shunt and galvanometer resistances?

16. Find the current which 5 Léclanché cells (in series), each having a resistance of 2 ohms and an E.M.F. of 1·47 volts, can send through a circuit comprising a galvanometer of 20 ohms resistance, shunted with a $\frac{1}{9}$th shunt, there being 10 ohms in a resistance-box connected in series with the circuit.

17. A pair of feeder mains, each half a mile long, have to deliver 100 kilowatts at 440 volts. What cross section must they have so that the loss in them may not exceed 5 % of the power delivered? (1 cubic inch of copper has a resistance of $\frac{2}{3}$rd microhm.) (Prelim. 1902 of the City and Guilds.)

18. State Ohm's Law, and say whether it applies accurately to varying or alternating currents as well as to steady currents. If not, why not? (Prelim. 1902.)

19. What is meant by 'drop' on electric conductors? How does the cross section of a conductor, and the current passing through it, affect the drop? How is the

importance of a certain drop in a given case affected by the voltage of the circuit? (Prelim. 1901.)

20. If the resistance of a cubic inch of copper is 0·66 microhm, and the diameter of each of a pair of wires be 0·064 inch, what length of circuit can be used so that the drop shall be 2 % when the pressure between the wires at one end is 200 volts, and the current flowing through lamps connected between the wires at the other end is 2 amperes? (Prelim. 1901.)

21 An electric glow lamp taking 0·5 ampere when supplied with 100 volts at its terminals is connected with 100-volt constant-pressure mains by means of 2 leads having together a resistance of $\frac{1}{3}$rd ohm. What will be the current through this lamp connected alone, and also when 1, 2, 3, 4, 5, and 6 exactly similar lamps respectively are turned on in parallel with the first, assuming that the resistance of the carbon filament remain constant at all currents? (Prelim. 1901.)

22. Three lengths of cable, of which the resistances are respectively 0·035, 0·025, and 0·013 ohm, are connected in parallel and used to carry a current of 80 amperes. How much of this current flows through each of the three cables, and what is the P.D. between the ends of the combination? (Prelim. 1901.)

23. What is the approximate resistance of 1 mile of No. 16 S.W.G. (0·064-inch diameter) high conductivity copper wire? What current will flow if its ends are connected with a pair of terminals having a P.D. of 50 volts? The resistance of 1 inch cube of copper = $\frac{2}{3}$rds microhm. (Prelim. 1903.)

24. A pair of cables, each 100 yards long, supply 350 amperes to a distributing-box, and the 'drop' in the cables is 5 volts. What would be the 'drop' if the current was reduced to 225? (Prelim. 1903.)

25. Why are shunts for sensitive galvanometers usually $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the resistance of the instrument? Of what material should such be made? Give reasons for your answers. (Prelim. 1903.)

26. A group of ten 60-watt 110-volt lamps is 90 feet from the distributing-board. What must be the diameter of the wires so that the fall of pressure between board and lamps shall be 1·1 volts? (Prelim. 1903.)

27. How does the resistance of the following substances vary with the temperature:—Carbon, copper, glass, gutta-percha, iron, manganin, platinoid? (Prelim. 1897.)

28. A group of twenty-five 16-c.p. 100-volt lamps, each taking 0·55 ampere, are run from a dynamo 50 yards away. What must be the cross section of the cable if the 'drop' is not to exceed $\frac{1}{2}$ volt? (The resistance of a cubic inch of copper $\doteq$ 0·66 microhm.) (Prelim. 1897.)

29. A 90-volt 8-c.p. glow lamp in series with a resistance is placed across 100-volt constant-pressure mains. On applying a voltmeter between the lamp terminals to ascertain if the pressure is correct the light diminishes. Explain exactly how this occurs. (Prelim. 1899.)

30. How would you readily calculate the resistance of circuits made up of a number of separate known resistances joined in multiple arc? (Ord. T. and T. 1897.)

31. Calculate the value of the resistances required for the $\frac{1}{10}$th and $\frac{1}{20}$th constant-resistance shunts for a galvanometer of 5000 ohms resistance. (Ord. T. and T. 1897.)

32. What would be the current in milliamperes sent by a 10-cell bichromate battery through a resistance of 100 ohms, each cell of the battery having a resistance of 5 ohms? (Ord. T. and T. 1897.)

33. Describe the best forms and materials used for insulators for aerial telegraph lines. (Ord. T. and T. 1897.)

34. In a water-power plant the dynamo, which produces a fixed P.D. between its terminals of 120 volts, is 300 yards away from the house. The usual load consists of

200 100-volt 35-watt glow lamps. What size of leads should be used if the resistance of an inch cube of copper be 0·66 microhm? (Ord. 1897.)

35. A compound-wound dynamo producing a terminal P.D. of 150 volts is used to charge 60 storage cells, each having an E.M.F. of 2·2 volts and a resistance of 0·001 ohm. If the leads joining the dynamo and cells have a resistance of 0·2 ohm, what will be the current generated? (Ord. 1897.)

36. The key for a Wheatstone bridge makes two contacts in succession. What are the circuits that are closed by each of these contacts, and is there any reason for closing one before the other? (Ord. 1897.)

37. You are required to construct a resistance-box for ordinary use. What material should the wire be composed of? What resistance would you make the coils have? What gauges of wire would you employ for the different coils? How would you adjust them? And what arrangement would you construct for enabling the number of coils in the circuit to be altered in the ordinary use of the box? (Hons. Sect. I. 1897.)

38. Write down the names of the following elements in the order of their conducting power for electricity:—Gold, aluminium, carbon, copper, iron, bismuth, platinum. (Elec.-Metall. Ord. 1897.)

39. State the general effects of alterations in temperature upon the electrical conductance of pure metals and of aqueous solutions. (Elec.-Metall. Hons. 1897.)

40. A gradual change is found to occur with ebonite. What is the cause, what effect does it produce, and how can it be prevented? (Hons. Sect. I. 1898.)

41. Give sketches of the parts of a resistance-box with which a resistance of 1 to 10,000 ohms can be obtained. Give a list of the respective resistances of the various coils, and describe in detail the precautions to be taken in the construction and in the use of the box, so that any resistance may be truly that indicated on the box. (Hons. Sect. I. 1899.)

42. Describe a 'universal shunt box,' and discuss its advantages and disadvantages as compared with the ordinary shunt box. (Hons. Sect. I. 1899.)

43. State what information you possess regarding the relative advantages of india-rubber, bituminous compounds, and impregnated fibrous materials as materials for insulating underground conductors. (Hons. Sect. III. 1899.)

44. A dynamo maintaining a constant pressure of 220 volts between its terminals supplies a power of 18,000 watts to a house 200 yards away. What must be the cross section of the copper of the leads so that not more than 4 °/ₒ of the power may be wasted in them? (Resistance of an inch cube of copper may be taken as 0·66 microhm.) (Prelim. 1899.)

45. Discuss the relative merits and demerits, electrical and mechanical, of the following materials for use in insulating the windings, commutator, brush-carriers, terminals, etc., of dynamos for pressure up to 500 volts:—Presspahn, mica, ebonite, vulcanised fibre, cotton, and paper varnished with shellac, or cloth treated with boiled linseed oil. Give some examples of cases where one or other material would be preferable. (Hons. Sect. II. 1900.)

46. If you had to select two forms of insulators for two aerial lines, one of which had to be erected in a dry and the other in a moist climate, what two forms would you select? (Ord. T. and T. 19.0.)

47. What is meant by the 'specific resistance' and 'specific electro-static capacity' of an insulating substance, and how can they be measured? (Ord. T. and T. 1901.)

48. What is a megohm, and also a microhm? If three lengths of cable having respectively an insulation resistance of 300, 400, and 500 megohms be joined in a continuous length, what will be the insulation resistance of the whole cable? (Ord. T. and T. 1902.)

49. Having given a galvanometer the coils of which have 5000 ohms resistance, state what will be the resistances of $\frac{1}{10}$ and $\frac{1}{100}$ shunts. If a current were flowing through the galvanometer coils, would the insertion of the $\frac{1}{10}$ shunt decrease the deflection to $\frac{1}{10}$th its previous value? Give a reason for your answer. (Ord. T. and T. 1902.)

50. If the diameter of an iron wire weighing 200 lbs. per mile be 121 mils, what will be the weight per mile of another iron wire whose diameter is 181 mils? The resistance of the 200-lbs. wire is 27 ohms; what is the resistance per mile of another wire weighing 400 lbs.? (Ord. T. and T. 1902.)

51. What mechanical and electrical qualities are required in (*a*) iron wire used for open telegraph lines, (*b*) copper wire for open telephone lines? (Hons. T. and T. 1902.)

52. Prove that the joint resistance of two resistances joined in multiple is the product of the two divided by their sum. (Hons. Teleg. 1902.)

53. If the resistance of a length of pure copper wire at 32° F. be 10 ohms, what will be its resistance at 52° F.; having given

Resistance at any temperature

$$t = R_t = R_{32}[1 + 0{\cdot}0023708(t - 32) + 0{\cdot}00000034548(t - 32)^2]?$$

What will be the resistance at 12° F.? (Ord. T. and T. 1903.)

54. Explain the qualities required in a 'resistance coil' employed for testing purposes. Give details of the materials that may be most suitably used and of the process of manufacture. (Hons. Teleg. 1903.)

55. Express the relations in regard to wires of circular section between :—(1) Resistance and diameter with equal lengths; (2) weight and resistance with equal diameter; (3) length and resistance with equal weights. A copper wire weighing 131 lbs. has 9·684 ohms resistance; an equal length of pure copper wire weighing 1 lb. would give a resistance of 1196·7 ohms. What, in comparison with pure copper, is the percentage conductivity of the wire? (Hons. Teleg. 1903.)

56. Four 200-volt glow lamps of 5, 8, 16, and 32 c.p. respectively are connected in parallel on a 200-volt circuit. Make a diagram showing the connections, and find the current passing through each lamp as well as the current required by the four. (Inefficiency of lamps 3·5 watts per candle.) (Prelim. 1904.)

57. The electrical installations of two detached buildings, one 200 and the other 700 yards from the source of supply, require maximum currents of 150 and 50 amperes respectively. What cross-sectional areas of copper should be employed in the supply circuits to give 'drops' of 5 and 7 volts respectively at full load? (Prelim. 1904.)

58. Calculate the resistance of one mile of copper conductor having a cross-sectional area of 0·137 sq. inch. (The resistance of an inch cube of copper between opposite faces is 0·66 microhm.) (Prelim. 1904.)

59. The specified resistance per mile of a wire 0·171 inch in diameter is 13·5 ohms. What is the diameter of a wire of same description and length, the resistance of which is 27 ohms? (T. and T. Ord. 1904.)

60. (*a*) What is to be understood by the term '$\frac{1}{100}$ shunt' of a galvanometer?
   (*b*) What proportionate value would it have relatively to the galvanometer?
   (*c*) 'G' being the resistance of the galvanometer, what will be the resistance between its terminals when the $\frac{1}{100}$ shunt is applied? (T. and T. Ord. 1904.)

CHAPTER V

ELECTRO-MAGNETISM

THE magnetic effect of an electric current has been referred to on page 35, but no attempt was made to indicate the principles underlying it. The actual reason why an electric current should invariably be accompanied by the presence of a magnetic field is as much a matter of hypothesis as the nature of an electric current is itself. All we know for certain is that an extremely close connection exists between electricity and magnetism, which is the foundation of the whole electrical engineering industry. We shall therefore now consider the form or forms taken by the effects above mentioned.

Magnetic Field of a Current in a Straight Wire.—Let us first take the simplest case, namely, the magnetic effect of a *unidirectional* or continuous current flowing in a *straight* conductor.

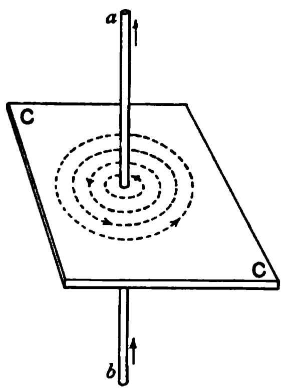


FIG. 50.—Field of a Straight Wire.

If such a conductor *ab* is passed perpendicularly through a hole in the centre of a sheet of cardboard CC and fine iron filings are sifted sparingly over the cardboard, then, on sending a current through *ab* in the direction shown by the arrow, the filings will arrange themselves in concentric circles around *ab*, thus showing that a magnetic field surrounds the conductor. The dotted curves represent the paths of the lines of magnetic force and are concentric with *ab*. The arrow-heads on these curves show the direction in which the lines of force act or flow when the current flows in the direction from *b* to *a*.

If the direction in which the current flows is reversed, the direction taken by the lines of force is also reversed. The stronger the current in *ab*, the greater will be the number of lines of force produced,

i.e. the stronger will be the magnetic field and also the greater will be the distance to which the lines radiate. Now though in Fig. 50 only an element, so to speak, of the magnetic field is indicated, due to the current flowing in *ab* at the point where the plane of the cardboard cuts the conductor perpendicularly, yet it must be remembered that the same effect is produced at every other point along *ab*.

Hence whenever a continuous current of electricity flows through a straight conductor, this conductor is completely surrounded along its whole length by a cylindrical magnetic field concentric with it.

If a conductor, carrying a sufficiently strong current, be dipped into iron filings, a quantity of these will adhere to it. This is of course owing to the lines of force trying to take the easiest and shortest path, which is now through the filings closest to the conductor.

Hand Rule for Directions of Field and Current.—Perhaps the simplest and most easily remembered rule for determining the direction of the lines of force for any direction of current is that shown in Fig. 51, and is as follows :—

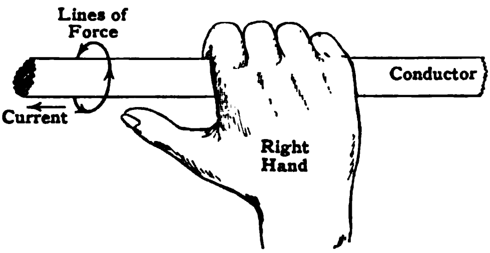


FIG. 51.—Hand Rule for direction of Field due to a Straight Current.

Grasp the conductor with the right hand in such a way that the thumb, when turned away from the hand, points in the direction in which the current is flowing; then the direction along the fingers towards their tips is that of the lines of magnetic force.

In Fig. 51 the reader is looking at the back of the hand; but if instead it had been the palm, the same rule being observed, then the current would be flowing along the conductor from left to right, and the direction of the lines of force set up would just be reversed.

Magnetic-Needle Rule for Direction of Current.—We can now understand the behaviour of a freely suspended or pivoted magnetic needle when placed near a conductor carrying a continuous current. Remembering the fact that whenever two different magnetic fields are in the vicinity of and are capable of influencing one another, one being fixed and the other movable, the latter will always tend to move into such a position as will cause the two fields to have one common path in one direction. Now let Fig. 52 represent, in plan and elevation, a conductor *c* running north and south and carrying a current which flows in the direction from N to S over the magnetic needle *ns*;

then, in order that the lines of force due to *ns* and the current in *c* may have a common direction and path, the north-seeking pole *n* of the needle must turn towards the east, E, which it does. If the direction of the current in *c* is reversed, then the pole *n* turns towards the west, W. These actions will each be reversed if the wire is under the needle, and it will be seen that they form a useful method of finding the direction of a current in a conductor, if a magnetic needle is available.

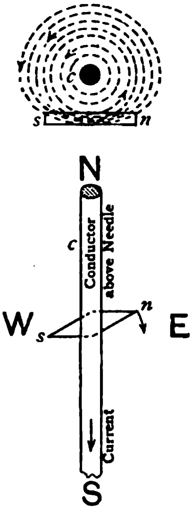


FIG. 52.—Deflection of Needle by Current in Straight Wire.

Electro-dynamic Action between Conductors carrying Currents.—The fundamental principles set forth in the preceding pages will enable us to see how two neighbouring conductors, carrying current, will affect one another. Let *ab* and *cd* (Fig. 53) be two conductors carrying currents, which flow in the same direction, as indicated by the arrows. Then a magnetic field will be created around each conductor, but the usual form of circular lines of force concentric with their respective conductors will be distorted. Now in the space between *ab* and *cd* the lines due to each will meet, flowing in opposite directions. The opposition which they thus meet with will cause all those which would meet to be diverted along an easier path, viz. that shown, embracing both conductors, by the outer curved lines, and in a direction indicated by the arrow-heads on these curves.

Further, the tendency of lines of force to find the shortest path, *i.e.* the one of least resistance, will cause a force to be exerted tending to bring *ab* closer to *cd*, which is the only way in which their paths can be shortened. If *ab* and *cd* were to approach one another so close as to touch, the outer paths would take the ordinary circular concentric form. We thus have the following rule:—*Two parallel conductors will attract one another, if the currents flowing in them are flowing in the same direction.* The rule will of course apply either to two totally different currents and conductors, or to two different portions of the same circuit carrying the same current.

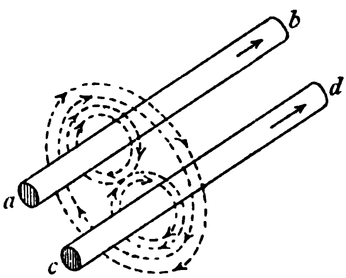


FIG. 53.—Electro-dynamic Effect of two Parallel Currents in same Direction.

If the currents flow in opposite directions in the conductors *ef* and

gh, as in Fig. 54, the lines of force due to the current in each conductor still continue to encircle it, but those of each field now have a common direction in the space between the conductors. The lines of force now tend to push one another aside, and in their endeavour to maintain a path concentric with their conductors these last-named are repelled away from one another. We therefore have the following rule :—*Two parallel conductors will repel one another if the currents flowing in them are flowing in opposite directions.*

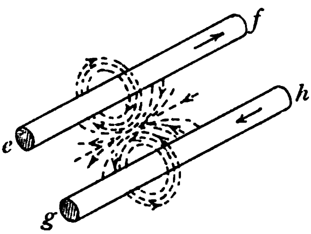


FIG. 54.—Electro-dynamic Effect of Opposite Currents, etc.

Though the fields and conductors are shown in perspective in Figs. 53 and 54, it must be understood that they act in planes perpendicular to the length of the conductors at every point in their length.

The reader will now be able to see the way in which oblique circuits, or those crossing one another, will act on one another. Let *ac* and *bd* (Fig. 55) be two conductors crossing one another obliquely at *o*, and carrying currents the directions of which are shown by the arrows. If A indicates attraction and R repulsion, then the conductors will experience a force or forces tending to make them turn about *o* as a centre and tending to cause them to close up and coincide. In reality they will tend to move so that *a* and *b* approach one another, as also *c* and *d*; and this motion will tend, not only to make the currents and conductors parallel, but also the currents to flow in the same direction.

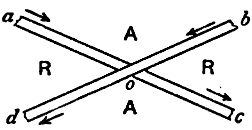


FIG. 55.—Dynamic Action of Oblique Circuits.

Magnetic Field of a Current in a Coiled Conductor.—We may now consider the form of the magnetic field produced by a continuous current flowing in a helical conductor, and which can be at once deduced from the foregoing principles. Let Fig. 56 represent a side sectional elevation, through a vertical diameter, of a continuous spiral conductor *c* of three turns wound on, say, a brass tube T.

If the current flows round the conductor in the direction indicated by the arrows, then by the hand rule given on page 123 the lines of force produced in a vertical plane around each conductor *c* at this point will tend to flow, as shown by the arrow-heads on their circular paths, concentric with *c*. For simplicity, only one line of force is shown in Fig. 56 around each conductor, but there would be several, the number depending on the current strength. Now it will be observed that all the lines have a common direction inside the helix,

as at *h*, and also outside it, as at *d*, but that between the turns, as at *a*, they have opposite directions.

At such points as *a*, therefore, the lines of force of two adjacent turns tend to neutralise one another, whereas at *h* and *d* respectively the lines of force have a common resultant line of force, which is really a tangent to the curves at these points, and is nearly parallel to the axis of T. For clearness this line is represented by NFS, and the direction is similar to that of the component lines producing it. The number of such resultant lines of force NFS depends on the number of lines around each conductor, *i.e.* on the current strength. Thus the stronger the current the greater the number of lines of force flowing through T, *i.e.* the interior of the helical coil, and emanating from the end N. These lines complete their paths outside the coil, some at a considerable distance from it, and re-enter again at the end S.

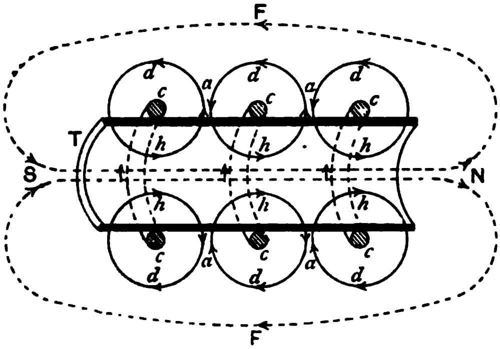


FIG. 56.—Field of a Helical Current.

The south-seeking end of a freely suspended magnetic needle will be attracted toward the end N and repelled from end S. Hence, from the rules on page 4, the end N must be a north-seeking magnetic pole and S a south-seeking pole. But we see precisely the same general distribution of lines of force in an ordinary bar magnet (Fig. 2, p. 5). Consequently a spiral coil or helix carrying a continuous current is a form of bar magnet.

Magnetic Field and Polarity of a Solenoid.—In Fig. 56 we have merely indicated the principle underlying the production of the magnetic field due to a helical conductor, but not the actual distribution of such a field. Referring to Fig. 57, let an insulated conductor be wound round some *non-magnetic rod or core* so as to form a helix of several turns as shown. Such an arrangement is commonly termed a *solenoid*, and if a continuous current be sent through it the magnetic field will take approximately the configuration shown in Fig. 57.

Now the current flowing in the solenoid in the direction indicated by the arrows will, according to what has already been said above, produce a field the lines of force of which all flow through the centre of the solenoid and out at the end region N. They will then

complete their paths through the air outside the solenoid and enter it again at the end region S. The end N is therefore the north-seeking pole, and S the south-seeking pole, of the solenoid. We therefore have the following rule :—*If on looking axially through a solenoid the current is flowing in the same direction as that in which the hands of a clock move (i.e. clockwise), then the end nearest the observer will be a south-seeking pole.* The converse is also true, namely :—*If on looking axially through a solenoid the current circulates round it counter-clockwise, then the end nearest the observer will be a north-seeking pole.* The above rules are true irrespective of whether the turns of the solenoid form a *right-* or a *left-handed* helix, and are depicted diagrammatically in Fig. 58.

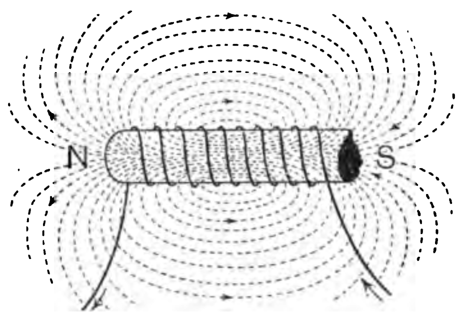


FIG. 57.—Distribution of Solenoid Field—Coreless.

Now it will be noticed in Fig. 57 that all the lines of force pass through the interior of the solenoid at the centre of its length, *i.e.* its equator, where they are therefore the most dense. Between the centre and ends they emerge from the sides of the solenoid, and only comparatively few leave and enter the extreme ends. This is due to the endeavour of the lines of force to find the shortest and easiest path, the direct result of this being that free magnetism is exhibited along the whole length of the solenoid except its central region, and that the poles are not at the extreme ends. A solenoid with a non-magnetic core, such as this, is but little used in practice, so that we will now pass on to the consideration of the effect of substituting a magnetic core instead.

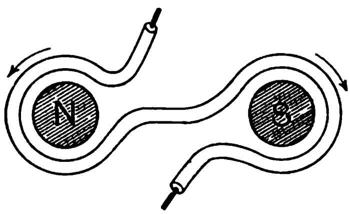


FIG. 58.—Polarity—Two-core.

A solenoid having a core of magnetic material is usually termed a solenoidal electro-magnet, and Fig. 59 shows the very marked alteration in the distribution of the magnetic field by such an addition. Since any magnetic material has many times the conducting power for lines of force that air has, the easiest path now for the lines is through the *whole length* of the interior or core, from the ends of which nearly all emanate, completing their paths in the usual way through the air out-

side. Since very few lines leak out sideways, the poles are practically at the ends, and their strength is far greater than those of the arrangement of Fig. 57. In all cases the strongest points of any magnetic field existent in a non-closed or non-continuous magnetic

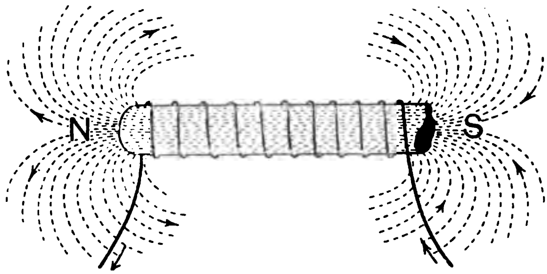


FIG. 59—Field of a Cored Solenoid.

conductor are those points from which the greatest number of lines of force tend to leak out into air; in other words, the points at which the greatest amount of 'free' magnetism exists. Such points are termed the poles of the field (*vide* p. 5), and these are not usually at the extreme ends of the magnetic conductor.

Consequent Poles.—A bar of magnetic material may, however, be wound in a special manner so that when magnetised more than two poles are produced. Fig. 60 shows such an arrangement of a bar of iron, say, wound with, what may be regarded for simplicity, three coils A, B, and C. Applying the rule given on page 127 for the

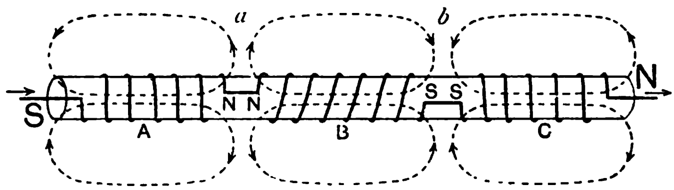


FIG. 60.—Consequent Poles.

direction of current indicated in the coils, we see that A and B will each produce a north pole N at *a*, while B and C will each give a south pole S at *b*. These are called 'consequent poles,' and the direction of the magnetic lines of force are shown by the dotted lines. There is therefore 'free' magnetism at the extreme ends of the bar S and N as also at *a* and *b*; in other words, there are two north and two south poles. Consequent poles are met with in all dynamos having double and multiple magnetic circuits.

Relation between Current and Magnetic Force Produced.—Having seen, in the preceding pages, that the flow of an electric

current is invariably accompanied by the production of a magnetic field or lines of magnetic force, and also the general form of the field so produced in several instances, we are now in a position to consider the relation which exists between the strength of the current and the intensity of the magnetic field produced.

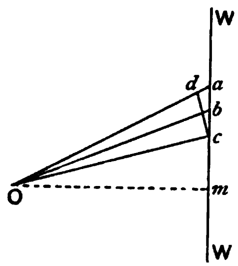


FIG. 61.—Intensity of Field due to current in a Straight Wire.

Let WW (Fig. 61) be a very long straight wire in which is flowing a current C, the return being so far away as to exert no magnetic influence in the vicinity of WW.

To find the intensity of the magnetic field at any point O, due to the current C in WW, we will first consider the intensity at O, due to a very short length *ac*. Join O*a*, O*c*, and O to the mid-point *b* of *ac*. Draw *cd* and O*m* perpendicular to O*b* and WW respectively.

Then the intensity I_e of the magnetic field at O, due to the short length or element *ac*, is directly $\propto$ *cd*, and also to C, and inversely $\propto (Ob)^2$. Hence

$$I_e \propto \frac{cd \times C}{(Ob)^2}.$$

Now the wire WW is made up of a large number of very small elements such as *ac*. Consequently the total magnetic force at O due to the *whole wire* WW will be the sum of all the effects or quantities, such as the above, of as many elements as compose the whole wire; or, the total magnetic force I at O can be shown to be

$$I \propto \frac{2C}{Om} \text{ absolute units,}$$

where C is the current in absolute electro-magnetic measure, and O*m* is the perpendicular distance in centimetres.

The foregoing considerations show us why a freely suspended magnetic needle (p. 124) tends to turn at right angles to a conductor carrying a current; for, the magnetic force at all points being perpendicular to the conductor, its direction of action must be everywhere a tangent to a circle concentric with the wire, and having its plane perpendicular to the length of the wire. By means of the preceding fundamental proposition we may now deduce results of great importance in connection with looped conductors.

Let PQR be a wire, bent into a circle, and carrying a current C which enters and leaves at P.

To find the total intensity I at the centre O of the circle due to the whole loop we may again consider a short length or element *ac*.

Join ac, and from its mid-point b draw bO, which is therefore the radius r in cms. of the circle and perpendicular to ac (by Euclid).

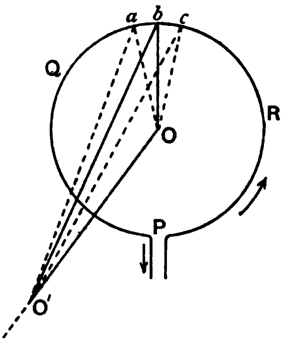


FIG. 62.—Intensity of Field due to current in Looped Conductors.

Now the intensity I_e of the magnetic field at O due to ac is evidently, by the above results,

$$I_e \propto \frac{ac \times C}{(Ob)^2} \propto \frac{ac \times C}{r^2}.$$

But the circle PQR is made up of such elements as ac, which are all at the same distance from the centre O. Hence the magnetic force at O due to the whole wire is

$$I \propto \frac{PQR \times C}{r^2} \propto \frac{2\pi r \times C}{r^2} \propto \frac{2\pi C}{r}.$$

If the current flows through n turns wound close together, instead of only through one, then

$$I \propto \frac{2\pi n C}{r}.$$

Similarly, the intensity of the magnetic force at any point in the axis of the circular coil may be found. Thus :—Draw the axis O′O of the loop perpendicular to its plane, and through the centre O. Join $O'b$, and let $O'O = x$ in centimetres.

Then $O'Ob$ being a right-angled triangle, by geometry we have

$$(O'b)^2 = (O'O)^2 + (Ob)^2 = x^2 + r^2,$$

or

$$(O'b) = \sqrt{x^2 + r^2} = (x^2 + r^2)^{\frac{1}{2}}.$$

Hence the intensity of the magnetic field at O′ due to the element ac is

$$I_e \propto \frac{ac \times C}{(O'b)^2} \propto \frac{ac \times C}{(x^2 + r^2)}.$$

This force, however, acts in a direction perpendicular to the plane passing through O′ and b; and its component along the axis O′O, which is the direction we are most concerned with in practice, is

$$I_e \propto \frac{r}{\sqrt{(x^2 + r^2)}} \times \frac{ac \times C}{(x^2 + r^2)} \propto \frac{r \times ac \times C}{(x^2 + r^2)^{\frac{3}{2}}}.$$

But the sum of the several quantities similar to that last given for each of the elements such as ac composing the loop gives the total resultant force I along the axis O′O.

$$\therefore \quad I \propto \frac{r \times 2\pi r \times C}{(x^2 + r^2)^{\frac{3}{2}}} \propto 2\pi C \times \frac{r^2}{(x^2 + r^2)^{\frac{3}{2}}} \propto 2\pi C \frac{r^2}{\sqrt{(x^2 + r^2)^3}}.$$

Magnetising Force.—The above result, important in itself, leads

us to an extremely important fundamental relation, as follows:— Let SS (Fig. 63) be a very long solenoid of comparatively small diameter, consisting of a number of turns (T) of insulated wire wound closely and uniformly upon a tube of non-magnetic material. Let the mean radius of the turns or winding, whether consisting of one or more layers, be r cms. from the axis ab. If a current C flows through the solenoid, the total intensity of the magnetic field, *i.e.* the magnetic force at some point O on the axis ab, near the centre of the solenoid, will be given by the sum of as many such terms as

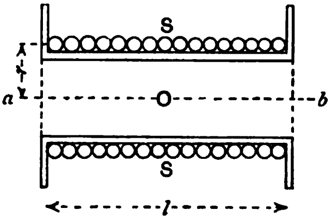


FIG. 63.—H for Solenoid.

$\frac{2\pi Cr^2}{(x^2+r^2)^{\frac{3}{2}}}$ as there are turns T on the solenoid. Each turn, the plane of which is at a different axial distance x from O, exerts a magnetic force which is represented by such an expression as the above, this force decreasing with the distance of the turn from O.

If l is the length of the solenoidal winding, then the sum of all the magnetic forces at O due to the same current in each of the individual turns can be written $\frac{4\pi CT}{l}$ absolute units. This is almost universally denoted by the letter H, and is called the *total magnetising force of the solenoid.* But 1 ampere $=\frac{1}{10}$ of an absolute unit of current, and if C is the current in amperes, we have

$$H=\frac{4\pi CT}{10l}=\frac{1 \cdot 257CT}{l},$$

or $H=1 \cdot 257 \times$ ampere turns per centimetre length of axis, where l is in centimetres and the product CT is called the *ampere turns.*

It may here be mentioned that for a given solenoid, H will be a constant for all combinations of C and T which make the product CT constant. Thus 1 ampere through 100 turns will produce the same magnetising force H as 5·0 amperes through 20 turns. The value for H obtained from the above relations is only true for solenoids which are very long compared with the length of diameter, and for points on the axis. The magnetic force inside a solenoid is greatest in the centre of the solenoid, and is a little greater near the inner turns than on the axis.

If the solenoid is about 15 diameters long, the variation of the magnetic force inside to within about one-quarter of the length of axis from each end is not greater than about 1 % of that at the centre. The falling off between these points and the ends is due to

the demagnetising action of the ends of the solenoid on the magnetic field within. It may here be noted that, since the interior of the solenoid is of non-magnetic material, the value of the magnetic—or magnetising—force H is the same as the number of lines of force per square centimetre at the centre and for a certain distance either side of the centre, depending on the ratio of the length of the solenoid to its diameter.

Magnetic Circuit.—Assuming that the reader has already perused Chapter I. on magnetism, he will readily realise the meaning of many of the terms or phrases used in the present one. We shall, however, have occasion to again allude to some, and deal with others more fully, in the following pages. Now, from considerations dealt with so far, the reader cannot fail to see that whenever a current flows either in a straight or a coiled conductor, the space surrounding it is the seat of the so-called *magnetic field* created by the current, and which completely disappears as soon as the current stops. At every point in this magnetic field a perfectly definite *magnetic force* is set up, which has not merely a certain fixed magnitude or intensity for a given current strength, but which also has a definite direction, acting along lines commonly termed lines of magnetic force, or, more briefly, *lines of force.* Thus the space surrounding any conductor carrying a current is pervaded by lines of magnetic force, which are invisible, but whose presence can be made apparent by, for instance, iron filings or a magnetic needle, in the manner already indicated.

Lines of magnetic force are continuous unbroken lines throughout their entire length, and for the sake of convenience in treating the subject they may conventionally be supposed to have a material existence and flow in definite number along a certain path in a given direction. In a similar manner it has been found convenient to deal with an electric current (*vide* p. 35); and as in this latter case the path taken by it was termed an *electric circuit,* so also *the path taken by lines of force is called a magnetic circuit.* A magnetic circuit cannot, in many cases, be so well defined as an electrical circuit, but there is nevertheless a most remarkable similarity between them. Leakage from the main path or circuit occurs with each; namely, of lines of force with the former, and of current in the case of the latter. This leakage obeys the same kind of law in each instance; namely, that it follows paths of least resistance, and occurs most at points in the main circuit which offer most resistance. In Figs. 57 and 59 it will be seen that the magnetic circuit is most indefinite, rather less so in Fig. 5, and well defined in Fig. 6. Whatever form, however, a magnetic circuit takes, its function is to carry the lines of force, and, as in the case of

an electric circuit, its resistance can be made almost anything we desire.

Now it is customary to speak of the total number of lines of force threading through the cross section of a magnetic circuit at any point in its length as the *magnetic flux*, though some people term it the total induction in the circuit. The reader is strongly recommended to use the expression *flux* for this total number of lines in order to avoid any possible confusion with another term, namely, *induction-density* or *flux-density*, which is otherwise called by some people the induction. This induction-density is the number of lines of force passing through 1 square cm. or 1 square inch of cross section of the magnetic circuit, and is usually denoted by the block symbol B.

Magneto-motive Force.—At this stage it may be convenient to introduce a somewhat different form of magnetic circuit to that hitherto indicated, by means of which other well-known quantities connected with a magnetic circuit may be dealt with.

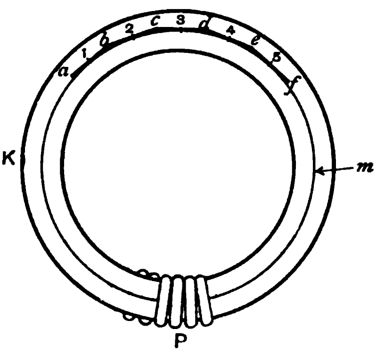


FIG. 64.—Solenoid Circuit on Coreless Ring.

Fig. 64 shows the form in question, consisting of a circular ring K of non-magnetic material having a circular cross section and closely overwound with contiguous turns of insulated wire in one or more layers. For convenience, only a few turns of the winding, which completely envelops the ring, is shown at P. Thus we have a circular or endless solenoid in the form of a closed ring, possessing no poles. The magnetic field set up by the current forms a circular magnetic circuit, the mean path m of which is the mean perimeter m of the ring K. Now let m be divided throughout its length into a large number of parts or elements ab, bc, cd, . . ., etc. of lengths l_1, l_2, l_3, etc. respectively; and let the magnetic forces at the centres 1, 2, 3, . . ., etc. of these elements, resolved in the directions of these latter, be h_1, h_2, h_3, . . ., etc. Then $h_1l_1 + h_2l_2 + h_3l_3 + \ldots$, etc. throughout the whole length of m is what is termed, in mathematical language, *the line integral of the magnetic force*, or commonly the *magneto-motive force* (usually abbreviated to the letters M.M.F.), along the line m. If now our solenoid is uniformly wound, which we have assumed it to be, the magnetic force is the same at the centre of each of the very short elements, or, in other words, it has a

uniform value in the direction of the mean path of the magnetic circuit.

Hence in this case we have

$$h_1 = h_2 = h_3 = \ . \ . \ . \ \text{etc.} = \text{H},$$

the magnetising or magnetic force due to the solenoid.

$$\therefore \qquad \text{M.M.F.} = \text{H}(l_1 + l_2 + l_3 + \ . \ . \ .) = \text{H}l,$$

where the sum of all the elements l_1, l_2, l_3, etc. of the mean path is equal to the length l of this path. Now on page 130 we saw that the total magnetic force due to the whole wire, at any point at a distance r from the axis of a straight wire carrying a current C, was $\frac{2\text{C}}{r}$ units.

If we draw a circle round the wire of radius r from its axis, this circle will represent the path of a line of force of length l.

Hence by the preceding proposition the line integral of the magnetic force right round this circle, *i.e.* the

$$\text{M.M.F.} = \frac{2l\text{C}}{r} = \frac{2\pi r 2\text{C}}{r} = 4\pi\text{C}.$$

Hence the M.M.F. along the line m (Fig. 64), which threads through T turns of the magnetising coil P, is

$$\text{M.M.F.} = \frac{4\pi\text{CT}}{10} = 1{\cdot}257\text{CT},$$

where C is now expressed in amperes, 1 ampere being $= \frac{1}{10}$ of a C.G.S. unit of current. Thus we see that unit M.M.F. is given by $\frac{1}{1{\cdot}257}$, or 0·795 of an *ampere turn*. But we have already seen that the

$$\text{M.M.F.} = \text{H}l = \textit{total} \text{ magnetising force},$$

where l is the mean length of the magnetic circuit. Therefore the magnetising force per cm. of mean length of the magnetic circuit

$$\text{H} = \frac{\text{M.M.F.}}{l} = \frac{4\pi\text{CT}}{10l}.$$

Magnetic Potential.—We are now led to a stage at which it is convenient to consider another quantity connected with any magnetic circuit, and which, unfortunately, is much more difficult of conception. This is *Magnetic Potential*. Now in the transformation of any one kind of energy into another kind, a certain force is invariably exerted, resulting in a certain amount of work being done. The latter is therefore a measure of the former. On page 15 we defined a unit magnetic pole, and the intensity of any magnetic field is measured by the force in dynes which it exerts upon such a unit pole. We have also seen (p. 17) that 4π lines of force emanate from a unit magnetic pole. Consequently one ampere turn in C.G.S. measure creates unit pole.

Now the fundamental definition of magnetic potential is that it is measured by the work done in ergs in moving a unit magnetic pole against the magnetic forces. Hence if a unit pole travels along any magnetic circuit surrounded by one turn carrying one ampere, the work done = 4π ergs, which is a measure of the magnetic potential created by that one current turn. Thus the total magnetic potential of such a circuit, for instance, as shown in Fig. 64 is $4\pi CT$, where C is the current in C.G.S. units flowing through T turns. In other words, the line integral of the magnetic force round the mean path m (Fig. 64), *i.e.* the M.M.F., is the work done in taking a free unit magnetic pole once completely round. Thus the total difference of magnetic potential in a magnetic circuit is equal to the M.M.F. acting on that circuit.

As in the case of electricity we have seen (p. 49) that no current can flow unless there is a *difference* of electric potential, so in the case of magnetic fields no lines of force are produced and flow unless there is a *difference* of magnetic potential. It will therefore be seen that magneto-motive force—the extreme difference of magnetic potential in a magnetic circuit—is an exactly similar quantity to electro-motive force—the extreme difference of electric potential in an electric circuit: a M.M.F. causing a flow of lines of force, an E.M.F. causing a flow of current.

Magnetic Permeability.—We have already seen that *all substances conduct* electricity to a certain extent,—some very readily, others very badly,—and that their conductance was one of degree compared with some substance taken as a basis. Conversely, all substances offer a certain resistance to the passage of electricity, this resistance being likewise one of degree. In magnetism we have precisely the same kind of behaviour; for all substances conduct lines of force to a certain extent,—some very readily, others very poorly,—and this magnetic conductance, as we may term it, is one of degree only, compared with a substance (in this case, *ordinary air*) taken as a standpoint and unity. Conversely, therefore, all substances offer some resistance to lines of magnetic force, which resistance is also one of degree merely.

Now whenever a M.M.F. acts on any substance whatsoever it sets up an effect termed *magnetic induction*, and the quality of a substance in virtue of which this effect takes place is termed its *magnetic inductivity* or *permeability*. Thus if the *same* M.M.F. produces a greater flux in a substance A than in another one B of exactly the same form, A would be said to have a greater magnetic permeability than B.

For iron and steel (in all forms), nickel, cobalt, manganese, chromium, cerium, titanium, many ores and salts of these metals, and for oxygen

the magnetic conductance, or, as it is sometimes called, the *permeance*, is greater than that of air, *i.e.* greater than 1. Such substances were termed by Faraday *paramagnetic*, while all other substances, including liquids, which conduct magnetic lines more poorly than air, he termed *diamagnetic*.

Of the paramagnetic materials, soft annealed Swedish charcoal iron, very hard Allevard steel, mild cast-steel, and ordinary soft wrought- and cast-iron are the most important and widely used materials for magnetic purposes at the present day.

Now, as in the case of electricity,

$$\text{electric conductance} = \frac{1}{\text{electrical resistance}},$$

so

$$(\text{magnetic conductance or permeance}) = \frac{1}{(\text{magnetic resistance or reluctance})}.$$

The magnetic permeability, usually represented by the letter μ, is the magnetic conductance of a magnetic circuit of unit length and unit cross-sectional area; and it is the reciprocal of specific magnetic resistance, which may be denoted by ρ.

Hence $$\rho = \frac{1}{\mu}, \text{ or } = \frac{1}{\rho}.$$

Laws of Magnetic Reluctance or Resistance.—These are similar to the laws given on page 69 for electrical resistance, namely, magnetic reluctance or resistance R is :—

1. Directly proportional to the length l of magnetic circuit.
2. Directly proportional to the specific magnetic resistance ρ of the material composing that circuit.
3. Inversely proportional to the cross-sectional area S of the circuit.

In symbols, we have

$$R = \frac{l\rho}{S} = \frac{l}{S\mu}.$$

Law of the Magnetic Circuit.—Now in an electrical circuit we have seen (*vide* p. 66) that

$$\text{the total current} = \frac{\text{the total E.M.F. acting}}{\text{the total electrical resistance}}.$$

Likewise, in a magnetic circuit we have

$$\text{the total flux} = \frac{\text{the total M.M.F. acting}}{\text{the total magnetic resistance}}.$$

Expressing this most important fundamental relation in the usual symbols, we find that if a given M.M.F. causes a total number of lines of force N to flow through a circuit of reluctance R,

then $$N=\frac{\text{M.M.F.}}{R}.$$

Now consider the form of magnetic circuit depicted in Fig. 64, consisting of a circular ring (of iron, for instance) of circular cross section, overwound uniformly with insulated wire. If a magnetising force H sets up a M.M.F. which produces an induction-density B, and, further, if the mean length of the magnetic circuit be l, its cross section S, and its permeability μ,

then $$N=\frac{\text{M.M.F.}}{R}.$$

But $$R=\frac{l\rho}{S}=\frac{l}{\mu S}, \text{ and M.M.F.}=Hl, \text{ also } N=BS.$$

$\therefore$ $$BS=\frac{Hl}{l\rho/S}=\frac{Hl}{l/\mu S}=\mu HS,$$

or $$B=\mu H.$$

This is a relation of great importance inasmuch that it provides us with the means of determining the permeability μ of magnetic materials; for $\mu=\frac{B}{H}$, and both B and H can be determined experimentally.

Again, since $$N=\frac{\text{M.M.F.}}{R},$$

and $$\text{M.M.F.}=Hl=4\pi CT\div 10,$$

where C is the current in amperes flowing through T turns,

therefore the flux $$N=\frac{4\pi CT}{10\dfrac{l}{S\mu}} \text{ C.G.S. lines of force.}$$

This last equation and that for B above are the two fundamental relations pertaining to magnetic circuits. The former, as it is here written, is strictly true for such a magnetic circuit as shown in Fig. 64, but when applied to such a one as shown in Fig. 6, supposing the magnetic field to be produced by a coil or coils of wire wound on the two limbs of the U magnet, carrying a current, then the value for R requires modification.

Here we are dealing with three materials—the hard steel of NS, the air-gaps, and the soft iron armature A.

If suffixes m, g, and a respectively denote the various quantities connected with these three parts of the circuit,

then $$R=\frac{l_m}{S_m\mu_m}+\frac{l_g}{S_g\mu_g}+\frac{l_a}{S_a\mu_a},$$

where l_g = the sum of the two air-lengths either side of A,

and $\mu_g=1$ for these gaps.

Hence
$$\text{flux } N = \frac{4\pi CT}{10\left\{\frac{l_m}{S_m\mu_m} + \frac{l_g}{S_g} + \frac{l_a}{S_a\mu_a}\right\}} \text{ lines.}$$

This formula was introduced by Hopkinson, and is the one used in the design of dynamos and electro-magnetic mechanisms. It may be written in a general form, namely,

$$N = \frac{4\pi CT}{10\Sigma\frac{l}{S\mu}},$$

where the symbol Σ denotes the sum of all such terms as $\frac{l}{S\mu}$ for any number of parts composing the circuit.

Before going further it may be well to familiarise the reader with the preceding principles by taking a few numerical examples, as follows :—

Example 1. A solenoid 10 inches in length is wound on a wooden rod 2 inches diameter, with 2000 turns of wire. If a current of 0·5 ampere passes through it, what is the value of the magnetising force and induction-density and flux near the centre ?

Since magnetising force $H = \frac{4\pi}{10} \cdot \frac{CT}{l}$,

and in our case $l = 10'' = 10 \times 2{\cdot}54 = 25{\cdot}4$ cms.,

where 1 inch = 2·54 centimetres,

$$\therefore \quad H = \frac{4 \cdot \pi \cdot 0{\cdot}5 \cdot 2000}{10 \times 25{\cdot}4} = 49{\cdot}5 \text{ C.G.S. units.}$$

Again, since the solenoid has a non-magnetic core, the induction-density B near the centre is the same as H, so that

$$B = H = 49{\cdot}5 \text{ lines per square cm.}$$

But the sectional area s of the core $= \frac{\pi d^2}{4} = \frac{3{\cdot}1416 \times (2 \times 2{\cdot}54)^2}{4}$.

$$\therefore \text{ the flux} \quad N = BS = 49{\cdot}5 \times \frac{3{\cdot}1416 \times (5{\cdot}08)^2}{4} = 1002 \text{ lines.}$$

Example 2. If, in the preceding question, the core was of good soft wrought-iron having a permeability $\mu = 300$, what would be the induction-density and flux in the core ?

Since $B = \mu H$,

by substitution we have

$$B = 300 \times 49{\cdot}5 = 14{,}850 \text{ lines per square cm.}$$

$\therefore$ the flux

$$N = BS = 14{,}850 \times \frac{3{\cdot}1416 \times (5{\cdot}08)^2}{4} = 301{,}000 \text{ lines.}$$

Example 3. A closed magnetic circuit of mild cast-steel has a mean length of 50 cms., with an average cross-sectional area of 20 square cms. It is wound with 1000 turns of wire, which carry a current of 5 amperes. Find the value of the magnetising force, flux, and induction-density in the magnetic circuit if its permeability = 125.

From page 134 we see that the magnetising force

$$H = \frac{4\pi CT}{10l} = 1{\cdot}257 \times \frac{5 \times 1000}{50} = 125{\cdot}7 \text{ C.G.S. units.}$$

Hence the induction-density

$$B = \mu H = 125 \times 125{\cdot}7 = 15{,}712{\cdot}5 \text{ lines per square cm.}$$

$\therefore$ the flux $\qquad N = BS = 15{,}712{\cdot}5 \times 20 = 314{,}250$ lines.

Example 4. In the last question, what would have to be the number of ampere turns to produce a total flux of 50,000 lines of force in the same steel ring, the permeability μ being = 3000?

Since N = 50,000, we have

$$B = \frac{N}{S} = \frac{50{,}000}{20} = 2500 \text{ lines per square cm.}$$

Hence the magnetising force

$$H = \frac{4\pi CT}{10l} = \frac{B}{\mu} = \frac{2500}{3000},$$

and $\therefore$ the ampere turns

$$CT = \frac{10l \, . \, 2500}{4\pi \, . \, 3000} = \frac{10 \times 50 \times 2500}{12{\cdot}57 \times 3000} = 33.$$

From Examples 3 and 4 it will be seen that while in the former instance 5000 ampere turns are required to produce an induction of 15,712 lines per square cm., in the latter only 33 ampere turns are needed to give an induction of 2500 lines per square cm.

In other words, $\frac{1}{150}$th of the number of ampere turns will give $\frac{1}{6}$th of the induction for the two values in question. This is due to the enormous decrease in the value of μ as the induction in the iron rises.

Open and Closed Magnetic Circuits.—In practice, two main classes of magnetic circuit are met with, namely:—(1) *Closed or non-polar magnetic circuits*, or those in which the lines of force flow round a *complete* iron path; (2) *open or polar magnetic circuits*, or those in which the continuity of the iron path is broken by an air-space. One form is quite as important as the other in the practical applications made of them, but it should be remembered that the former type of circuit exhibits practically no *free* magnetism (p. 5), and consequently no

magnetic leakage if the flux-density is not too large. In the *open* type all the flux produced is *free*, thereby creating definite polarity. Further, that a greater number of ampere turns is required to produce a given flux in the *open* than in the closed type for the same induction B in each case. Closed magnetic circuits are little used with continuous currents of electricity, but they are extensively used in alternating current appliances.

Strikingly similar as the considerations pertaining to electric and magnetic circuits appear to be, there is, however, a great difference, inasmuch that in the former its electrical resistance at constant temperature is independent of the current strength, whereas in the latter the magnetic resistance is wholly dependent on the induction-density B in the circuit.

Variation of Magnetic Induction with Magnetising Force.—We may now consider how the magnetisation, *i.e.* the amount of magnetism or number of lines of force, of a piece of magnetic material varies when the magnetising force producing it varies. It is unfortunate that there is no simple relation between magnetising force applied and induction produced, and that every specimen of magnetic material possesses a different relation.

Now, without actually describing any of the several methods of measuring the magnetic induction produced by given magnetising forces, and which can be much better obtained from a reference to practical books on the subject (as, for instance, the author's *Practical Electrical Testing*), we may assume that we can readily measure both quantities. A table showing the various values of magnetising force $H \propto$ current and the corresponding inductions B can then be compiled, which is useful. The most convenient way, however, of seeing at a glance how B varies with H is to graphically depict it in the form of a 'curve,' obtained by plotting[1] to two rectangular axes the values of H and B.

Let OC and Od (Fig. 65) be two such straight lines at right angles, or rectangular axes, as they are called, each being divided into any convenient number of equal parts (not shown). We will suppose that the magnetic material under consideration is very good soft iron, and that H (which $= \frac{4\pi CT}{10l}$) varies from O to a value O$d = 150$ in C.G.S. units. If the iron has not been previously magnetised, the value of the flux, which is directly proportional to the flux-density B, will = O before any magnetising force H is applied.

[1] A detailed description of curve-plotting will be found in the author's work above mentioned.

Next take any pair of values of B and H from the table, and mark the point P_1 where the two perpendicular lines through the points representing these values B_1 and H_1 on the respective scales intersect. Repeating the operation for other pairs of values B_2H_2, C*d*, etc., we obtain a series of points P_1, P_2, *g*, etc. Then on joining these latter points a curve similar to OP_1P_2g is obtained, which shows very clearly how B varies with H at any stage of the magnetising process. For the material in question the length OC may represent a value of B = 18,000 lines per square centimetre of cross section corresponding to O*d*, *i.e.* H = 150 C.G.S. units.

Now from page 132 we see that the magnetising coil by itself, with

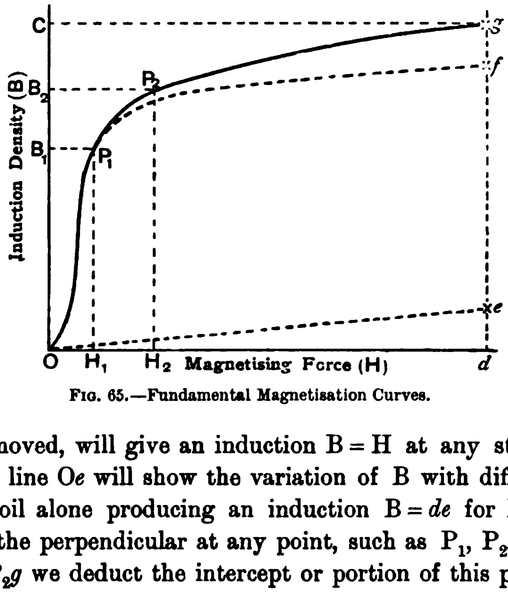


FIG. 65.—Fundamental Magnetisation Curves.

the iron removed, will give an induction B = H at any stage, so that the straight line O*e* will show the variation of B with different values of H, the coil alone producing an induction B = *de* for H = O*d*. If, then, from the perpendicular at any point, such as P_1, P_2, etc., on the curve OP_1P_2g we deduct the intercept or portion of this perpendicular included between the line O*e* and axis O*d*, the series of points so obtained will lie on the dotted curve O*f*. This latter curve O*f* is what may be termed the net effect of the material alone. In materials having a high permeance, *gf*, which = *de*, is so small compared with *gd* that the curve OP_1P_2g is taken as the true magnetisation curve of the specimen.

Studying this last-named curve further we see that, just at first, for a very small value of H (= OH_1) there is a very rapid increase of induction B (= OB_1). The curve then begins to bend sharply from this point P_1 to some other point P_2, resulting in only a small increment of induction B_1B_2 for double or treble as much magnetising force H_1H_2. From P_2 the increase of B is very small for very large

increases of H, and at g we see that increasing H only adds very little to B, indicating, as is shown by the curve Of becoming nearly horizontal, that the iron is almost 'saturated,' and is unable to allow many more lines of force to pass through it. The main increase at this stage is due to the coil alone.

Fig. 65 therefore is a most important object lesson, in that, since energy is expended in applying a magnetising force, it is obviously uneconomical to magnetise soft iron to a value lower than that represented by OB_1, or to a value higher than OB_2, which latter value is over

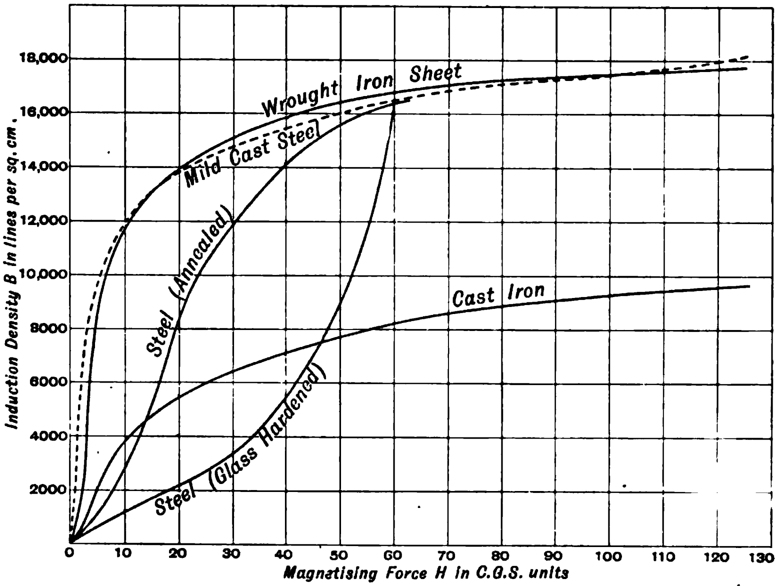


FIG. 66.—B and H Curves of Magnetisation.

the brow of the curve and near the saturation point. The lines Of and Oe would, if the magnetising force H were increased sufficiently, meet in a point which would be the saturation point of the iron, and at which its permeability would be the same as that of air.

Fig. 66 affords a means of readily comparing the shapes of the curves of magnetisation of some of the most important magnetic materials employed in electrical engineering. The curves are plotted on what is termed *squared paper*, to the scale of the axes shown; the heights of all points on the curves, measured vertically, and otherwise called *ordinates*, represent flux-density, while their distances, measured horizontally, and otherwise termed *abscissæ*, represent magnetising or magnetic force. The curves are those for averagely good quality materials as employed at the present time, and it will at

once be seen that of the substances represented, and, indeed, of all magnetisable materials, wrought-iron sheet and mild cast-steel are not only much alike in their magnetic property, but are also the best; further, that the harder a material is, the poorer is its magnetic quality, *e.g.* steel untempered but glass-hardened is extremely hard, while being one of the worst materials to employ for electro-magnetic purposes. To see that this is the case, we have only to compare the induction-density in the various materials produced by a magnetising force H = say 10 C.G.S. units. For wrought-iron sheet and mild cast-steel B is about the same, viz. 12,000 lines per square cm.; while for cast-iron B = 4000, annealed steel 3000, and glass-hard steel 1000. For higher values of H, however, the case is different: *e.g.* when H = 60, the value of B with the materials, excepting cast-iron, is about the same, viz. 16,000 to 17,000; B for cast-iron now being only half as great, or about 8000. The order in which they can be placed in increasing magnetic merit therefore depends on the value of H used.

The shapes of the curves for the two most important of all magnetisable substances, viz. wrought-iron sheet and mild cast-steel, show us that it is uneconomical in magnetising force employed to use these materials at a lower value of B than 11,000 or a higher one than about 17,000, these two values being represented by points just under and over the brow of the bend of the curves respectively. In fact, we see that increasing H from 40 to 120, or threefold, only increases B from 16,000 to about 18,000, or $\frac{1}{8}$ more induction. In other words, these materials are approaching their magnetic saturation points for H = 40 or 50.

Variation of Magnetic Permeability with Magnetic Induction.—Now it was stated on page 140 that although the resistance of an electrical conductor at constant temperature was independent of the strength of the current flowing in it, the reluctance of a magnetic conductor changed with every alteration of the induction-density in it. This change in the conducting power is well illustrated in Fig. 67, which gives the curves between μ and B for the three most important magnetisable materials of average good quality as met with at the present day.

Comparing the permeabilities (μ), *i.e.* the specific magnetic conductances, we see that this reaches a maximum of about 500 for cast-iron at B = 1800, of about 2100 for wrought sheet-iron at B = 6000, and of about 3000 for mild cast-steel at B = 4000. Further, that from B = about 12,000 and upwards there is no difference between mild cast-steel and the wrought-iron sheet. These

curves, particularly in the case of the two last-named materials, show in a marked way how rapidly the permeability diminishes from the maximum values as the induction- or flux-density increases. We shall see presently that not only does the value of μ vary in the way shown in Fig. 67 when the magnetising force is gradually increased, but that it also depends on the *direction* of and method of applying the force immediately preceding any determination.

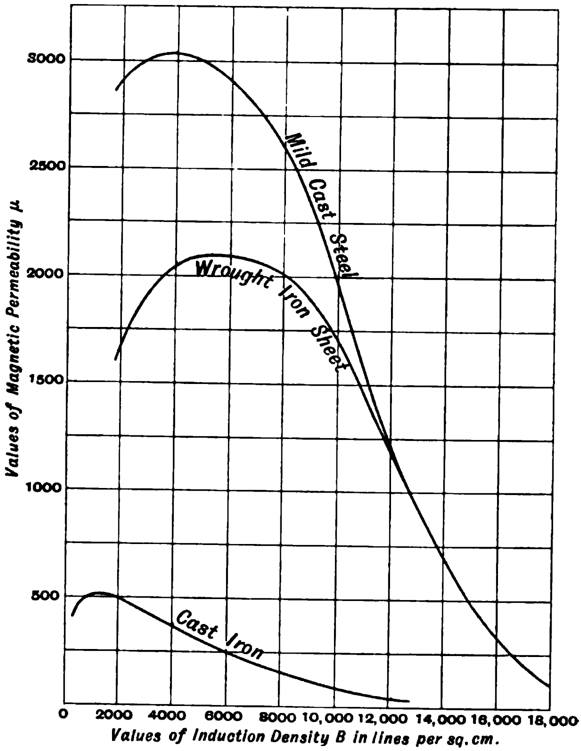


FIG. 67.—μ-B Curves.

Messrs. J. Sankey and Sons of Bilston make a special soft iron for the armature cores of dynamos, which for $H = 2{\cdot}14$ gives $B = 6000$ and $\mu = 2800$, but μ as high as 3510 has been obtained by them for $B = 5000$.

Magnetic Hysteresis.—We may now deal with an important phenomenon met with in the magnetisation of magnetic substances. Take, say, annealed steel, in the form of an endless ring (Fig. 64), overwound uniformly with an insulated current-carrying conductor. If this ring, to commence with, be devoid of magnetism, then on

gradually applying a continuously increasing magnetising force H (in one direction, usually taken as + ^{ve}) by means of an electric current in the coil, the induction density B will increase in the way already described, and the curve OA will be obtained.

Now, without stopping the current, let it and the resulting magnetising force H be gradually reduced from A to O again. The curve between H and B will be found to follow some such path as AB. On reversing the direction of flow of the current and increasing it from O (but in what may be termed a − ^{ve} direction) to the same maximum value as before, the curve BCD will be obtained. If now, without breaking circuit, the magnetising force be reduced to O again, we get the curve DE; and lastly, by reversing the direction of current and increasing it from O to the same + ^{ve} maximum as at first, the curve EFA is obtained.

These operations, which constitute what is termed a *cycle* of magnetising force, give us the curve or loop ABCDEFA (Fig. 68), which is likewise known as a *complete magnetic cycle.* If the above ring consisted of soft, annealed wrought-iron instead of annealed steel, some such loop as *abcdefa* would represent the magnetic cycle produced by a cycle of magnetising force similar to that mentioned above. In fact, every magnetisable substance exhibits the same kind of phenomena whether in a greater degree as indicated by the curve ABCDEFA, or in a less degree by the curve *abcdefa.* In other words, the magnetic induction evoked in a substance by a cyclic magnetising force has a greater value at all points during the decrease of the force than during the increase of it.

Prof. Ewing, who first pointed out this lagging of the induction behind the magnetising force, *i.e.* the lagging of the magnetic effect behind the cause, has termed it *magnetic hysterēsis*; and the loop enclosing the particular area, the B-H curve of hysterēsis for the magnetic substance. Studying the phenomena of hysterēsis by means of the curve (say, ABCDEFA) we see that when H has been decreased to O, B still has a considerable value OB, which is termed the *remanence* or *retentivity.* To reduce the remanence to zero it requires the application of a demagnetising force or − ^{ve} magnetising force = OC, which is usually termed the *coercive force* or coercivity. The induction B changes its direction or reverses sign at the point C, and reaches a maximum value in this negative direction at D for a − ^{ve} value of H = the + value of H, which produced the + maximum induction at A. The return half DEFA of the curve is merely a repetition of the first half ABCD, OE, which = OB, being the − ^{ve} remanence, while OF, which = OC, is the + ^{ve} coercive force.

The foregoing considerations apply in a similar manner to the curve *abcdefa* for soft wrought-iron and to all other hysterēsis loops. Now, if the molecular theory of magnetism (p. 11) be accepted as the correct one, the molecules of the material will have all their like poles pointing in one direction during that part of the magnetic

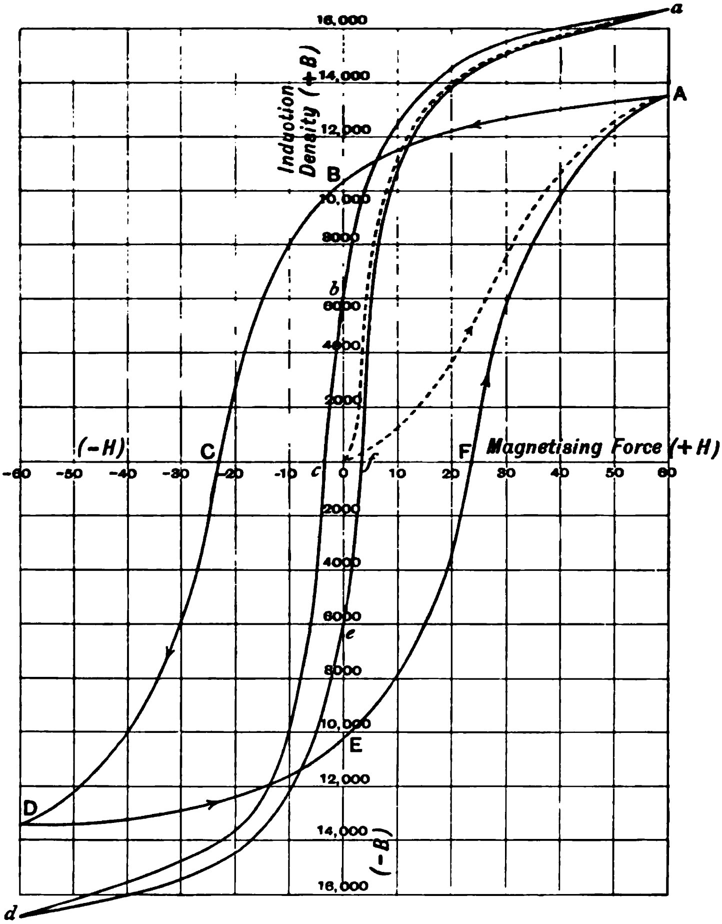


FIG. 68.—Hysterēsis Loop.

cycle EFAB, and in the opposite direction during the remaining portion BCDE. Consequently, energy must be expended and work must be done in causing this reversal of their direction. Further, we have just considered the effect produced on the magnetic induction by constantly varying the magnetising force in a systematic manner, so as to form a *cycle* of operations represented by the cyclic curve (Fig. 68). If this cycle of operations is repeated over and over again, as it

would be if an alternating current were used, the magnetising force is said to act *periodically*, and the magnetic induction in the specimen will go through a periodic cycle. Now, practical operation proves that at whatever rate the cycle is performed, heat invariably makes its appearance in the iron to some extent, whether in very small amount or otherwise. The energy thus appearing in the form of heat in the iron must result from the expenditure of energy in some other form, for *the law of the conservation of energy* tells us that *no energy is ever lost*, and that *energy is convertible one form into another*. Hence, whenever the phenomenon of magnetic hysterēsis occurs, energy is always expended and work is done.

Now if a magnetising force H produces a magnetic induction B, and this latter changes by a very small amount dB in the very small interval of time dt, the time rate of change of induction will be $\frac{dB}{dt}$.

Also if s is the mean cross-sectional area in sq. cms of the iron path having a mean length l cms, then it can be shown mathematically that the whole energy wasted in heat in the iron or absorbed by the iron, due to the hysterētic effect in the very small time dt

$$= \frac{sl}{10^7} \cdot \frac{1}{4\pi} \cdot HdB \text{ joules.}$$

Now the product $sl = V$, the volume of the iron in c.c. Hence the whole energy expended on the iron in the time limits of the integral

$$= \int \frac{V}{10^7} \cdot \frac{1}{4\pi} \cdot HdB \text{ ergs} = \frac{V}{10^7} \cdot \frac{1}{4\pi} \int HdB \text{ ergs.}$$

where the sign $\int$ or integral, in mathematical language, denotes the summation of the many changes in the term which follows during a period known as the time limits of the integral.

Now the term $\frac{1}{4\pi}\int HdB$ by itself represents the energy (in ergs) expended per unit volume (1 c.c.) of the iron core in one cycle of magnetisation, when the time limit of the integral $\int$ is the interval of time taken in making one complete magnetic cycle. Since also the loop is drawn to two axes representing H and B respectively, the integral or quantity $\int HdB$ taken over the limits of the whole cycle is the area of this loop. Hopkinson gives this area as also approximately equal to that of a rectangle, the sides of which are respectively equal to twice the remanence and twice the coercive force; *e.g.* in the curve ABCDEFA (Fig. 68), the value of $\int HdB$, or the area, would be approximately = the area $2OB \times 2OC = (BE \times CF)$. From a reference to the figure and from the preceding remarks it will be seen that the area of the loop, and therefore the value of

$\frac{1}{4\pi}\int HdB$, depends, in the first instance, on the kind of material in use, and this determines the values of the *coercivity* and *remanence*.

Mr. C. P. Steinmetz has determined empirically an equivalent to the above expression, in terms of the maximum value of the induction-density, which we will call $\hat{B}$, and a constant η depending on the kind of material, namely—

The energy (in ergs) expended per unit volume (1 c.c.) of the iron core during one complete cycle

$$=\frac{1}{4\pi}\int HdB=\eta\hat{B}^{1\cdot 6}.$$

This is sufficiently correct for all practical purposes, and the following values of the hysterētic constant η, which hold for inductions up to just over the brow of the magnetisation curve, may be taken:—

Best soft annealed Swedish charcoal-iron sheet	0·0015
Good soft wrought-iron sheet	0·0025
Ordinary soft wrought-iron bar	0·00315
Thin tin-plate	0·00290
Grey cast-iron	0·0150
Very soft annealed cast-steel	0·0032
,, ,, ,,	0·0045
,, ,, ,,	0·0085
Tool-steel, annealed	0·0190
Tool-steel, glass-hardened and tempered in cold water	0·0750

H. Maurach[1] has determined the value of the exponent x in Steinmetz's formula $w=\eta\hat{B}^x$ for different values of $\hat{B}$. The measurements were made by the ballistic method on a sample of transformer iron, and show that x decreases as B increases. He obtained values for x, which are given in the annexed table:—

TABLE X

H.	Probable Value of B.	x.
0·3	500	2·47
3·0	2,000	1·94
12·0	12,400	1·33
28·0	15,000	1·22

The decrease in the value of x is rapid between the first two values of H, and less rapid afterwards. The variation in the hysterēsis loss, which occurs in a rotatory and alternating field, is mentioned on page

[1] *Ann. d. Physik*, 6. 3, pp. 580-589, Nov. 1901.

149. F. Niethammer[1] has investigated the hysterēsis loss in an alternating field, and finds that the coefficient $\eta = 0{\cdot}00259$ when $B = 1400$; $\eta = 0{\cdot}00291$ when $B = 2700$; $\eta = 0{\cdot}00257$ when $B = 7600$; and $\eta = 0{\cdot}00368$ when $B = 13{,}600$. He further finds that the form of variation of such a current does not affect the value of η much. With rotatory fields, such as that met with in the armature of dynamos, he finds that η varies from $0{\cdot}00305$ to $0{\cdot}00119$ when B changes from 14,010 to 4495 respectively.

Expenditure or waste of energy due to the hysterētic effect, and usually termed hysterēsis loss, invariably occurs in all magnetisable substances when their magnetisation is *changed* or *reversed*, and however slowly the magnetic cycle is performed. The loss from hysterēsis is due solely to such change or reversal, and in no way depends on the construction of the magnetic circuit, *i.e.* whether it be solid or built up of the finest subdivision. The researches of Drs. J. and E. Hopkinson, practically confirmed by Steinmetz and others, show that for flux-densities not exceeding about 4000 or 4500 lines per square centimetre, the area of the loop, and consequently the hysterēsis loss, is the same whether the magnetic cycle is performed very slowly or at the rate of 100 cycles or more per second. Ewing has found that hysterēsis loss is considerably reduced by mechanical vibration, and also by rise of temperature; but the diminution from the latter effect is small within the limits of temperature met with in practice for electrical engineering appliances. Hysterēsis loss occurs in all electro-magnetic appliances using or producing intermittent or alternating current, also in the armature cores of direct-current dynamos in which a complete magnetic cycle takes place for each pair of poles in the field magnets per revolution. The vibration of the machine in this case, for example, considerably reduces the effective value of the hysterēsis loss, which in this and all other instances results in the production of heat in the iron.

It is instructive to compare the losses, caused by magnetic hysterēsis in various materials, given in the following table taken from the researches[2] of Prof. Ewing:—

[1] *Wied. Annalen*, 66. 1, pp. 29-48 (1898).

[2] 'Researches in Magnetism,' by J. A. Ewing—*Philosophical Transactions*, Part II. (1885).

[TABLE

TABLE XI

Material.	Hysterēsis Loss per c.c. for Strong Magnetisation.	
	In Ergs per Cycle.	In Watts per 100 Cycles per Second.
Very soft annealed iron	9,300	0·093
Less ,, ,, ,,	16,300	0·163
Hard-drawn iron wire	60,000	0·600
Annealed steel wire	70,500	0·705
,, ,, ,, glass-hardened	76,000	0·76
Pianoforte steel wire (annealed)	94,000	0·94
,, ,, ,, (ordinary)	116,000	1·16
,, ,, ,, (glass-hard)	117,000	1·17
Tungsten steel (oil-hardened) [1]	216,864	2·16

The hysterēsis loss is often expressed as so many *watts per lb.* xpended in overcoming hysterēsis if the iron were made to go through 100 cycles per second. In an extraordinarily good brand of iron made by Messrs. J. Sankey and Sons, of Bilston, for transformer work the following results were obtained:—

TABLE XII

Limits of B.	Hysterēsis Loss.		Permeability μ.	Magnetising Force H.
	Ergs per c.c. per Cycle.	[2] Watts per lb. at 100 Cycles per Second.		
1,000	...	...	1610	0·62
2,000	220	0·129	2560	0·78
2,500 [3]	...	0·185	...	...
3,000	410	0·242	3340	0·90
4,000	640	0·376	3880	1·03
5,000	910	0·535	4230	1·18
6,000	1200	0·706	4410	1·36
7,000	1520	0·895	4450	1·57
8,000	1900	1·120	4330	1·85
9,000	2310	1·360	4090	2·20
10,000	...	...	3790	2·64

Magnetic Lag.—Under this heading we must explain another phenomenon met with in electro-magnetism, but so far not considered. The phenomenon dealt with in the preceding pages is that of the

[1] Determined by Hopkinson, the material being that used for permanent magnets, and having a high retentivity.

[2] Watts per lb. per 100 cycles per second $= 0·000589 \times$ ergs per c.c. per cycle.

[3] This induction is sometimes taken as a standard condition for comparison. Messrs. Turner Bros., of London, supply 'improved non-ageing transformer sheets' which have a hysterēsis loss of 480 ergs per c.c. per cycle, or 0·28 watts per lb. at 100 cycles per second, when B=4000, which is unaffected by temperature up to 160° F.

difference in the value of the induction-density when the magnetising force has been *raised* to some particular value, and when it has been *reduced* to exactly the same value. This may conveniently be termed *static hysterēsis.* If, on the other hand, the magnetising force be altered to some different value, and be maintained at that value with great constancy, it is noticed that the induction-density gradually creeps to the new corresponding value, and finally remains constant in value. The creeping may take many minutes, and amount to several per cent of the final value. This 'time lag' of the induction has been termed 'magnetic lag,' or magnetic creeping, and, by Prof. Ewing, *viscous hysterēsis.*

There are, in addition, two other effects observable, namely, the apparent lag caused by the self-induction of the magnetising coil retarding the rise and fall of the current in it and the apparent lag met with in magnetising solid magnetic cores caused by the demagnetising effect of induced, eddy, or Foucault currents, as they are termed, flowing in the core, especially when the magnetic circuit is an open one (p. 139). The last effect depends on the self-inductive one, and both cease to act when the current reaches its steady value. Magnetic hysterēsis only becomes of real importance with intermittent or alternating current, and in appliances worked by the latter every endeavour is made to reduce it to a minimum by employing very soft iron, as little of it as possible, and as low a number of complete magnetic cycles per second as possible, coupled with a smaller induction-density than would be used with a continuous current. It should also be remembered that high permeability is not necessarily or invariably accompanied by small hysterēsis.

Electro-magnets.—We are now in a position to consider electro-magnets, and the form they should take for any particular purpose, which in a great measure depends upon the winding of the coils and the magnetic properties of the core. Such appliances are essentially intended to exert a force of attraction on, or a pull, causing the motion of, a piece of soft iron, commonly called the *armature.* The efficacy of the action must therefore depend on the amount of free magnetism available, and hence the presence of 'free' poles capable of exerting a force of attraction on the armature. Thus from principles already enunciated we see that the actuating portion of the electro-magnet must possess an 'open magnetic circuit' capable of being closed by the armature.

In practice we meet with both *slow-* and *quick-acting* electro-magnets, more particularly the latter, which is the kind required for 'time-recording' apparatus, telegraph instruments, etc. The requirements for obtaining rapidity of action are :—

1. The careful balancing of the moving parts, and by making these light and with as little inertia as possible.

2. The use of the best and softest iron obtainable for the magnetic circuit in order that it may possess maximum permeability, combined with minimum retentivity or residual magnetism. This last-named property causes the armatures of electro-magnets to stick to the poles, unless separated therefrom by a very small air-gap or its equivalent. For this reason the poles should be capped with a very small thickness of some non-magnetic material, such as copper or brass, which has the same effect as an equivalent thickness of air-space. The greater the gap or gaps the more rapidly will the electro-magnet acquire and lose its magnetism. Well-fitting, continuous magnetic circuits, even when made of the softest Swedish charcoal iron, always retain a large percentage of their magnetisation after the magnetising force has ceased. On breaking the magnetic circuit, however, most of this disappears, leaving what may strictly be termed the residual magnetism.

3. The use of polarised armatures, in which the movable soft iron armature is maintained in a magnetised condition inductively (*vide* p. 8) by a separate permanent steel magnet. The attraction between the poles thus induced in the armature, and those of the magnet cores, is delicately balanced by a spring, so that very feeble currents in the magnet coils suffice to overcome the balance and produce a rapid motion of the armature between fixed limits or stops. In this way great sensitiveness and rapidity of action is obtained in, for instance, the telephone bell, and relays used on long telegraph lines.

4. The use of short compact magnetic circuits, for a self-demagnetising tendency always exists in short non-closed cores, due to the poles being closer together, and tending to neutralise one another. Thus the shorter the magnetic circuit the more rapidly does it acquire and lose its magnetisation.

5. Minimum self-induction in the electro-magnet. For a complete explanation of the phenomenon of self-induction the reader is referred to p. 194 *et seq.* Suffice it here to say, that it is a property possessed by a coil of wire, whether surrounding iron or not, in virtue of which the current in the coil is unable to rise to its full strength, or die out, instantaneously. Since the self-induction of a current-carrying coil, of the form used in electro-magnets generally, is proportional to the permeability μ of the core, and also to the square of the number of turns in the coil, the rapidity of action will be increased principally by using fewer turns when this is possible.

Electro-magnets with movable armatures may be classified according to the range of motion of the latter into those of—(1) short range,

(2) moderate range, (3) long range; but it should be remembered that the range depends on the relative dispositions of the magnetising coils, and the iron parts of the magnetic circuit, and not on whether the coil is wound with many turns of fine wire or a few turns of thick wire. The force of attraction between the poles of an electro-magnet and its armature varies considerably with the range and construction, being greatest in (1) and least of all in (3). It is also generally the case that the stronger the pull the shorter the range, and *vice versa.*

In Fig. 69 we have a typical instance of a short-range electro-magnet capable of exerting a powerful pull over this range. It consists of two similar coils C, each wound with a number of turns of either silk- or cotton-covered copper wire on a bobbin, of which *f* are the flanges. The bobbins C are slipped over soft iron rods or *cores* I, as they are commonly termed, which are best screwed into a bottom cross-bar of soft iron (*y*) called the *yoke.* The *armature* A, or moving portion of the electro-magnet, consists of a soft iron bar of rectangular section sufficiently long to rather more than bridge across between the outside edges of the poles *n* and *s*. The coils C, C are connected in series with one another in such a way that a current flowing through them creates a north pole at *n* and a south pole at *s*, or *vice versa.* This is a form of electro-magnet largely used in electric bells and other appliances. The rationale of the action of the electro-magnet when a current flows through it is that the lines of force emanating from *n* flow into one end of A (if this be close enough), then through it and out of the other end into *s*, thus completing their path through I*y*I. The armature A, which is thus magnetised by induction, or becomes *polarised,* develops at its ends opposite polarity respectively to that of the poles *n* and *s*, and is consequently attracted (*vide* p. 4).

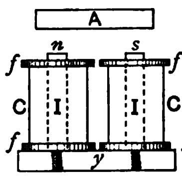


Fig. 69.—Ordinary Double-Coil Electro-Magnet.

Another way of regarding the action is that the lines of magnetic force which gather up in A exert a dragging force on it by reason of their ever-present tendency to shorten their path to the minimum. The lines thus behave like cords in tension, tending to pull A towards the poles *n*, *s*. Now principles already dealt with in the earlier stages of this chapter tell us that the force of attraction will depend on the strength of the poles *n* and *s*, and hence on the total number of lines of force emanating from them. For a given number of ampere turns provided by C, C the number of lines will be greater, the softer and purer the iron used for A, I, and *y*, and the larger the cross section and shorter the lengths of these parts. It is no use

making I, I large in cross section unless A and y are each at least equal in section to them, or *vice versa*. To get the best results out of any electro-magnet of a given form there should be the fewest number of joints in the magnetic circuit, and these should be faced so as to give the maximum amount of surface contact.

Fig. 70 illustrates what is often termed the *club-foot* electro-magnet, in which only one magnetising coil C is used. I is now the soft iron core proper, the yoke comprising not merely the part marked y, but in addition a soft iron bar or rod B, which helps to complete the magnetic circuit, and gives a south pole s. In this case the saving of copper wire is at the expense of a diminished pull on the armature A, otherwise the arrangement is more compact than that of Fig. 69.

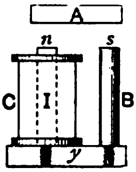


FIG. 70.—Club-Foot Electro-Magnet.

Another form in which only one coil C is used, and that on the yoke, is shown in Fig. 71. The yoke, which is really now the core I, is terminated by end-plates D, D, giving the poles n and s as shown.

This is a good arrangement, and is used to a large extent in starting switch resistances for electro-motors, and a number of other appliances.

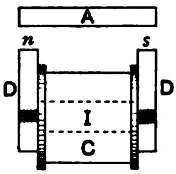


FIG. 71.—Electro-Magnet with Coil on Yoke.

Another form which is also used for the purpose just mentioned is indicated in Fig. 72, and is known as the *pot* or *iron-clad* electro-magnet. In this form the iron core is let into the bottom of an iron pot P, and is concentric with it. The magnetising coil C is slipped over this core into the pot, and is completely enveloped by it. Thus the upper end of the core forms one pole, while the whole rim of the pot forms the opposite pole, and is on the same level with the top of the central core n. The armature consists of a substantial soft iron disc or lid of the same diameter as the pot, and sufficiently thick. The iron pot is cut away at the side to show the coil C. The foregoing electro-magnets are instances of forms capable of exerting a strong pull over a short range.

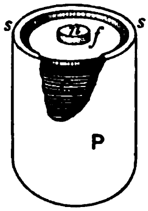


FIG. 72.—Pot Electro-Magnet.

A type of electro-magnet capable of exerting a medium pull over a moderate range is shown in Fig. 73, and is known as a *stopped solenoid*. In this the magnetising coil C is slipped over a fixed soft iron core E, which extends only a short distance up the coil. E is fixed to an iron yoke-piece yy, terminating in iron limbs L, L on opposite sides of the coil, which form poles of similar polarity. The armature A is attached to a soft iron plunger core I, capable

of being sucked into the coil C, the approaching ends of I and E touching when A touches the outer poles *n*, *n*. The arrangement is an instance of what is termed a double magnetic circuit, or two magnetic circuits in parallel, for the lines through IE divide at the yoke and flow up the right- and left-hand limbs L, L, then through AA to I again.

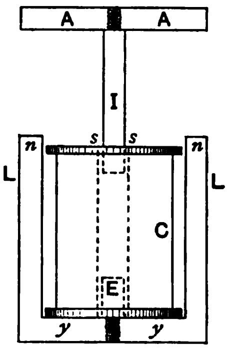


FIG. 73.—Stopped Solenoid.

To obtain a weaker pull over a longer range still, recourse may be had to a long solenoid (Fig. 74), sucking into it a still longer soft iron core I. The pull is greatest when the entrant end reaches the farther end of the coil. Sometimes the end of the core entering the coil is *coned* for a considerable length from the end in order to equalise more nearly the pull over the long range of suction. Sometimes the coils are wound in a conical manner to effect the same result. The force of suction or attraction which such a tubular coil or solenoid exerts upon its iron plunger core is not, in any position of the latter, nearly as great as that of an electro-magnet of the form shown in Fig. 69 for the same amount of metal used in its construction, and for the same current, but the range is much greater. Both of the last-named forms are largely used in electric *arc lamps*, as well as in many other appliances.

Now the attraction of a horseshoe-shaped magnet, or of that shown in Fig. 69, varies enormously with the position of the armature A, being very great when the latter is close to the poles, but diminishing extremely rapidly as the distance between armatures and poles is increased. Special devices of a mechanical nature have been introduced for the purpose of equalising this otherwise unequal pull on the armature, and they are called *equalisers*. Space, however, will not permit of a wider treatment of this important subject, and the student is therefore referred to such a work as *The Electro-Magnet*, by Professor S. P. Thomson, for greater detail.

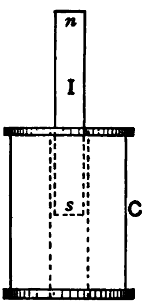


FIG. 74. — Long Solenoid, Long Range.

Electro-Magnets for alternating Currents may have any of the preceding forms, but special care has to be taken in constructing them, and they differ somewhat in detail from direct-current forms. In the last-named we are principally concerned with obtaining 'free' magnetism in certain magnitude by an induction-density in the magnetic circuit of something like 16,000 lines per square centimetre. We naturally desire to

obtain this result with the expenditure of as little electrical energy as possible, for part of such is spent continuously in overcoming the resistance (R) of the coils due to the term C^2R, and part in first momentarily creating the magnetic field. Now, if an instrument capable of measuring both continuous and alternating current equally accurately be placed in the circuit of an electro-magnet, it would indicate a smaller current when this was alternating than when continuous for the same E.M.F. Obviously, then, the electro-magnet offers extra resistance to the flow of alternating currents through it; but, although we cannot at this stage explain what is occurring, it may be stated that the extra resistance is of the form of a back E.M.F., caused by the phenomenon of *self-induction* in the electro-magnet (*vide* p. 194). Consequently an electro-magnet for alternating currents must be designed so as to allow the necessary current to flow through it, for on this depends its strength.

Owing to magnetic hysterĕsis, the loss of power due to which we have seen is $\propto B^{1 \cdot 6}$, the induction-density B in an alternating current electro-magnet is usually restricted to a maximum of about 10,000 lines per square centimetre. The iron circuit, including cores, yoke, and armature, should be made of the best soft iron, and carefully laminated, for if of solid cross section, *induced* or *eddy currents* will be set up transversely in the iron, and it will become very hot, perhaps sufficiently so to burn the insulation of the coils. This heat not only reduces the susceptibility of the iron, thus weakening the magnetic field, but it also represents an expenditure of energy which can only be minimised by the efficient lamination of the iron. Even when the laminations are ever so lightly insulated from one another, the strength of the eddy currents is reduced. Further, these currents tend to demagnetise the iron, so that this and the preceding remarks at once show us why an electro-magnet with a solid core is so much poorer in its action than if this core was laminated.

Lifting Power of Electro-Magnets.—After a reference to p. 10, Chap. I., the reader will realise that the lifting power of an electro-magnet depends on (*a*) its magnetic strength, (*b*) the shape of its poles, (*c*) its general form, (*d*) the form and nature of the armature attracted, (*e*) the area of contact, (*f*) the mass of the armature. Electro-magnets of the double-limb type, when properly designed, exert a force of attraction as high as 240 lbs. per square inch, with the cores *over-saturated* magnetically. In a paper on the 'Construction of Electro-Magnets,' by A. J. Conor,[1] the author points out that in electro-magnets with armature in contact, if B = the induction, S = sectional area in square centimetres,

[1] *Électricien*, 22, p. 344, 1901.

and F the tractive force in kilogrammes: then $B = 4965\sqrt{\frac{F}{S}}$ gauss (1 kilogramme = 2·204 lbs. (avoir.) and 1 gauss = 10^8 lines of force). A. Guénée, in an article on 'Industrial Electro-Magnets' (*Ind. Élect.* 9, Oct. 10, 1900), gives the best form (Fig. 75) of long-range electro-magnet as consisting of an ironclad coil, sucking a soft iron plunger N into its interior. The plunger works backwards and forwards through one end of the ironclad shell A, which is rather massive at the ends, and butts up against the other end of the shell. This back end of the plunger consists, for about one-third of the length CD of coil, of separated discs of soft iron E, E. The most powerful magnet made gave a constant effort of 650 kilogrammes, with a travel of 22 centimetres, total weight 207 kilogrammes, excitation 30 amperes at 220 volts.

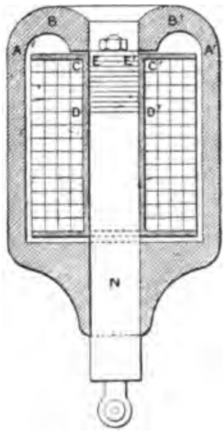


Fig. 75.—Guénée's Long-Range Electro-Magnet.

In an interesting discussion on 'Electro-Magnets for Lifting,' by E. B. Clark,[1] the author points out that rolling mills, locomotive and boiler shops are well suited for electro-magnetic lifting. The mass lifted should have a fairly smooth surface on which to apply the magnets, which latter for plate-work may comprise a group of rectangular poles,

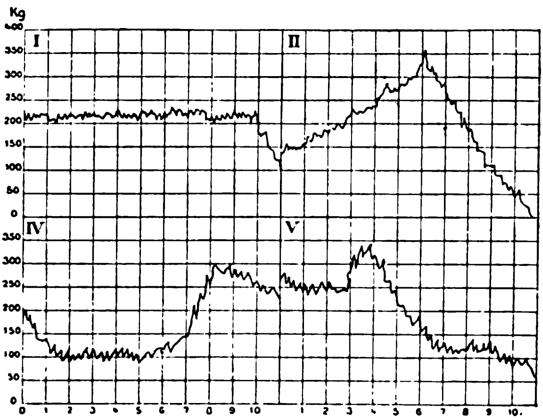


Fig. 76.—Curves for Guénée's Electro-Magnet.

say 12, each $3\frac{1}{2}''$ long and $5'' \times 1''$ in section, bolted to a soft iron plate

[1] *Amer. Elect.* 12, p. 558, 1900, and 13, p. 64. 1901.

provided with an eye-bolt for slinging from cranes. Each pole may be wound to a depth of $\frac{3}{4}''$, no bobbin being used. A lifting electro-magnet built up in this way, and weighing 300 lbs., should lift 27 times its own weight, and take about 4·4 amperes at 250 volts.

Uses of Electro-Magnets.—These are multitudinous, and the extreme importance of such appliances may be judged from a rough estimation that probably 75 per cent or more of all the various electrical engineering appliances and apparatus in existence employ an electro-magnet of one form or another, without which it would cease to exist. Another recent use to which the electro-magnet has been put in some modern marine yards, iron and other works, is its extensive employment for lifting, adjusting, and removing, etc., work to and from machine tools, and about the shops, thus effecting great economy in both time and labour (*vide* p. 157). In a recent article by Mr. F. C. Perkins[1] it was shown that in a certain instance the attractive power of the magnets was equal to a weight of 3901 lbs., the total power absorbed for this with a drill in addition was 1·3 h.p. In some steel-works in this country and the States, a single magnet is used for lifting as many as twenty steel or iron plates at a time, totalling some 3450 lbs.

Winding of Electro-Magnet Coils.—For a given iron core or magnetic circuit, we have seen (p. 137) that the number of lines of force passing through it depends on the number of *ampere* turns, and for a given current also, on the number of *turns* in the exciting coil. Naturally it is desirable to obtain these turns with minimum weight of copper wire used, and this leads us to considerations relating to the shape or form which the coil ought to have, and to other important details. Obviously it is possible to have two main forms of winding as shown at A and B respectively, Fig. 77. In A all the turns line up with one another in two directions at right angles, and large interstices, or air-gaps, are obtained at the side of the turns. In B the turns of any one layer lie in the interstices formed between the surface and points of contact of turns in the under layer.

Now from a mere inspection of these two forms of winding, Fig. 77, it is seen that in B a less depth of winding space is required than in A, but with a loss of one turn for every two layers. The fact, however, that in B the mean radius of the turns is smaller than in A, may more than compensate for the loss of the few extra turns, since the turns are, on the whole, closer to the magnetic axis or core of the coil (*vide* p. 131). In the case shown, B (Fig. 77), if a triangle

[1] *Électricien*, 27, pp. 17-19, Jan. 1904.

abc be drawn between the centres *a*, *b*, *c* of the three wire turns *a*, *b*, and *c*, this, by the geometry of the figure, is obviously an equilateral triangle. Drawing the perpendicular *af* we find that

$$\frac{af}{ab}=\frac{\sqrt{3}}{3}=\frac{1\cdot 732}{2}=0\cdot 866 \text{ (\textit{Euc.} Bk. i. 47),}$$

or

$$af=0\cdot 866ab.$$

If now d = outside diameter of the insulated wire, then

$$ab=3d \text{ and } \therefore\ af=0\cdot 866\times 3d.$$

Hence in form B $\quad t^1=af+d=2\cdot 598d+d=3\cdot 598d,$

whereas in form A $\quad t=4d.$

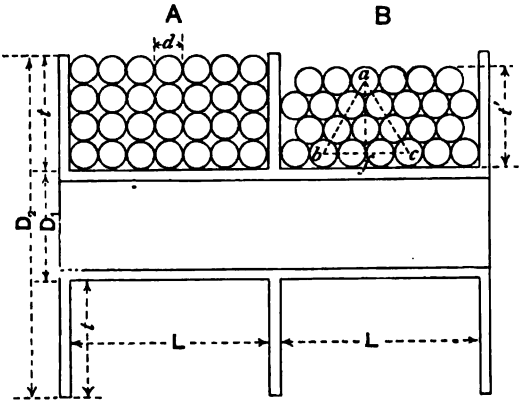


FIG. 77.—Section of Coil Windings.

It can therefore be seen that, for an equal winding depth ($t^1 = t$), one extra layer can be wound on B more than on A every 10 layers.

Thus while a total of 5 turns will have been lost in the 10 layers under form B, the extra layer mentioned above will have added 6. This difference, both in number of turns and weight of copper is so small that clearly it will make no appreciable error whichever form of winding A or B is taken for future discussion. Consequently we will consider A, although B, no doubt, is the usual form which the turns on a coil take in practice. Let the various dimensions be as indicated in Fig. 77, all in the same units—*inches*, or otherwise.

Further, let D = the mean diameter of the coil.

m = the length of a mean turn.

l = the total length of the wire in the whole coil.

T = the total number of turns in the whole coil.

x = the number of turns per layer.

y = the number of layers.

d = the diameter of the insulated wire.

To find the Total Length of Wire (l) in a Coil.—Given the diameter (d) of covered wire and size of winding space.

The number of turns per layer

$$x=\frac{L}{d},$$

and the number of layers $$y=\frac{t}{d}.$$

Hence the total number of turns on the bobbin

$$T=xy=\frac{L}{d}\times\frac{t}{d}=\frac{Lt}{d^2}.$$

Further, since the length of a mean turn

$$m=\pi D=\pi\tfrac{1}{2}(D_1+D_2),$$

the total length of wire on the coil is

$$l=mT=\frac{\pi(D_1+D_2)}{2}\times\frac{Lt}{d^2}=\frac{V}{d^2},$$

where all the symbols represent quantities in similar units, *e.g.* in inch or in cm. measure, and V = the volume of space occupied by winding

from the equation $$T=\frac{Lt}{d^2},$$

we have $$d=\sqrt{\frac{Lt}{T}},$$

which is therefore the diameter of the wire that would fill a coil of given dimensions with a given number of turns.

To find the Resistance (R) of a Coil.—Given the dimensions of the coil, the specific resistance (ρ) of the material with which it is wound, and the diameters d_1, and d of the bare and insulated wire.

We have just seen that the total length of wire on the coil is

$$l=\frac{\pi Lt(D_1+D_2)}{2d^2}=\frac{V}{d^2}.$$

Therefore, from p. 69,

$$R=\frac{l\rho}{A}=\frac{\pi Lt\rho(D_1+D_2)}{2Ad^2}=\frac{\pi Lt\rho(D_1+D_2)}{2\frac{\pi d_1^2}{4}\cdot d^2},$$

where the cross section of the wire

$$A=\frac{\pi d_1^2}{4}.$$

Hence $$R=\frac{2Lt\rho(D_1+D_2)}{d_1^2d^2}=\frac{4V\rho}{\pi d_1^2d^2}\text{ ohms},$$

ρ being in ohms per inch cube, and the other dimensions in inches, or ρ being in ohms per cm. cube, and the other dimensions in cms.

Now the increase in diameter of the bare wire due to insulation is $d-d_1$, which may or may not be small compared with d_1, depending

on the gauge of wire and nature of the insulation used, whether silk or cotton, etc.

If the increase of diameter due to insulation be so small compared with d_1 that it can be neglected, then $d = d_1$ approximately,

and therefore $$R=\frac{4V\rho}{\pi d^2 d_1^2}=\frac{4V\rho}{\pi d_1^4} \text{ ohms approximately,}$$

or $$d_1=\sqrt[4]{\frac{4V\rho}{\pi R}} \text{ approximately,}$$

which gives the diameter of the wire filling a given coil space V and offering a resistance R.

The last equation for R shows us that for a given winding space *the resistance is inversely proportional (approximately) to the 4th power of the diameter of the wire employed, the resistance of the coil is directly proportional to the volume of the coil.*

It can also easily be shown under the above assumption that d and d_1 are practically equal, and therefore that the resistance of a coil of fixed dimensions is directly proportional T_2.

To find the Weight (w) of Wire of given Diameter necessary to fill a Coil of given Dimensions.—First determine the total length of wire (l) on the coil from the relation given on p. 160. From reference to any wire table, as, for instance, those met with in price lists of wire and cable manufacturers, the number of feet or yards per lb. (k) for the diameter or gauge of iron in question can be seen.

Hence $$w=\frac{l}{k} \text{ lbs.}$$

It should here be noted that if k refers to the bare wire, the value of w will be the weight of metal in the coil, whereas it will be the weight of metal + insulation if k refers to covered wire.

The following figures are taken from the report of the Committee on Standards for Copper Conductors, and have been adopted by all the leading cable and wire manufacturers of this country.

High conductivity commercial copper weighs 555 lbs. per cubic ft. at 60° F., with a corresponding specific gravity = 8·912.

The average temperature coefficient = 0·00238 per 1° F. = 0·004285 per 1° C. Weight in lbs. per yard = 11·5625 × area in sq. ins. Resistance in standard ohms per yard = 0·000024044 ÷ area in sq. ins. Specific resistance ρ (per in. cube) of annealed copper = 0·00000066788 ohm at 60° F., and ρ (per cm. cube) = 0·0000016964 ohm at 60° F.

To find the weight (w) of metal in a coil, given l and d, in inches (say), we find that $\frac{1}{555}$ cubic feet or $\frac{1728}{555}$ cubic inches weigh 1 lb.

Also that the volume of copper on the coil

$$V_c = lA = \frac{\pi d^2 l}{4} \text{ cubic inches,}$$

therefore $$w = \frac{\pi \times 555}{1728 \times 4} \cdot d^2 l = 0 \cdot 2523 d^2 l \text{ lbs.}$$

If l is in feet and d in inches,

then $$w = 12 \times \cdot 2523 d^2 l = 3 \cdot 0276 d^2 l \text{ lbs.}$$

Relation of Diameters of Core and Coil.—It may be well to point out here that for a given E.M.F. available for sending current through a given coil, it is useless to try and effectively increase the magnetising force by adding layers of wire after reaching a certain radius. Obviously, by so doing, the resistance of the whole coil increases at a faster rate than the number of turns, since the turns are added in direct proportion to the addition of layers. The resistance of every added layer, instead of being equal to that of the last one, is greater because of the diameter, and therefore the length of wire in the layer being greater than in the preceding one. Thus for the same E.M.F. at its terminals the ampere turns, and therefore the magnetising force, actually diminish. For a given length of coil the practical limit of usefulness in adding layers is reached when $D_2 = 3D_1$ (Fig. 77), or when the outside diameter of the coil is about three times that of the iron core. Thus the thickness (t) of winding should be about equal to the diameter of the iron core, but there is no fixed rule for the length of core expressed in diameters long. It is common to meet straight forms of electro-magnets with cores ranging from 1 to 5 diameters long. This relation of length to diameter must necessarily depend on what the electro-magnet is intended to do.

Power Wasted in a Coil and its Rise of Temperature.—The considerations on page 57 at once show us that if a current of C amperes flows through a resistance of R ohms at the terminals of which there is a P.D. of E volts, the power expended

$$W = C^2 R = \frac{E^2}{R} \text{ watts.}$$

If the current is a continuous and steady one, Joule's law, p. 55, tells us that the whole of this power is spent in heating the coil. The resulting rise of temperature will go on until the rate of dissipation of heat due to radiation, conduction, and convection is equal to the rate of production, when the coil will remain at this constant or working temperature. For a given power expended, the final temperature will depend on the amount of external surface of the coil

exposed to, or in contact with, the air, *i.e.* the cooling surface; the thickness (t), Fig. 77, of the winding; the temperature of the air at the time; the emissivity for heat of the coil, *i.e.* the facility with which the coil, having the particular nature of surface in question, parts with the heat.

It is, of course, imperative that the final working temperature of any electro-magnet coil should not be too high, since not only might the insulation of turns be damaged, but the increase of their resistance might be sufficient to so reduce the strength of current which a given E.M.F. can send through that the magnetising force would be seriously diminished. If a temperature limit is fixed upon, a cooling surface proportional to the power wasted in heating the coil must be provided. A number of rules have been formulated for obtaining the rise of temperature in coils. Esson gives $\frac{1}{358}$ of a watt as the rate of emission per square cm. per 1° C. from surfaces consisting of double-cotton-covered wire varnished, allowing for facilities to cooling given by the bobbin ends and metal core.

If T° C. is the rise of temperature in degrees Centigrade, W the watts wasted in heat in the coil, and S the surface of the winding in square inches, then the rule is—

$$T^\circ \text{ C.} = 53{\cdot}5\frac{W}{S} = 53{\cdot}5\frac{C^2R}{S} = 53{\cdot}5\frac{E^2}{RS},$$

where R is the resistance of the coil (hot) in ohms.

Further, if R_1 is the resistance cold,

$$R = R_1 + \left(\frac{R_1}{100} \times \frac{T^\circ \text{ C.}}{2\frac{1}{2}}\right)$$
$$= R_1\left(1 + \frac{T^\circ \text{ C.}}{250}\right) \text{ ohms approximately.}$$

When T° is fixed at the commencement, Professor S. P. Thompson gives the following rules:—

If we assume that 90° F. (or 50° C.) higher than the surrounding air is the safe limit of temperature which may be used with a given electro-magnet coil, then for thick wire or series coils—

$$\text{Maximum permissible current} = 0{\cdot}95\sqrt{\frac{S}{R}} \text{ amperes,}$$

and for thin wire or shunt coils—

$$\text{Maximum permissible pressure} = 0{\cdot}95\sqrt{SR} \text{ volts.}$$

Roughly speaking, experience dictates that any given coil should have a radiating surface of at least 1 square inch per watt wasted, though preferably from 2 to 3 square inches per watt, in order to keep it comparatively cool.

The following are a few examples of the application of the preceding relations :—

Example 1.—A coil of wire, having a winding length of 4″ and an outside diameter of 3″, is wound on a cylindrical surface 1″ in diameter. What must be the diameter of the covered wire in order that 1000 turns may be wound on?

From page 160 we have $T = \frac{L \cdot t}{d^2}$,

whence the diameter required $d = \sqrt{\frac{L \cdot t}{T}}$.

Substituting, we therefore have

$$d = \sqrt{\frac{4 \times 1}{1000}} = \sqrt{0 \cdot 004} = 0 \cdot 0632 \text{ inch.}$$

Example 2.—In the last question, if the diameter of the bare wire $= 0 \cdot 050''$, what would be the resistance of the coil if wound with copper wire, and what the power wasted in it if 5 amperes passed through it?

From page 160 we have

$$R = \frac{2L \cdot t \cdot \rho (D_1 + D_2)}{d_1^2 d^2}.$$

Therefore, by substitution, we have the required resistance

$$R = \frac{2 \times 4 \times 1 \times 0 \cdot 00000066788 \times 4}{(\cdot 05)^2 \times (\cdot 0632)^2} = 2 \cdot 14 \text{ ohms.}$$

Therefore the power wasted in heat is

$$W = C^2 R = (5)^2 \times 2 \cdot 14 = 53 \cdot 5 \text{ watts.}$$

On applying the formula on page 163 for the rise of temperature of the coil due to this waste of power, namely,

$$T^\circ \text{ C.} = 53 \cdot 5 \frac{W}{S},$$

since the radiating surface of the coil $= L \pi d_2 = 4 \times \pi \, . \, 3 = 12\pi$ sq. ins. Therefore the rise of temperature of the coil

$$T^\circ \text{ C.} = 53 \cdot 5 \frac{W}{S} = 53 \cdot 5 \times \frac{53 \cdot 5}{12\pi} = 76^\circ \text{ C.}$$

Example 3.—How many turns of No. 22 S.W.G. copper wire (diam. $= 0 \cdot 028''$) double-cotton-covered to $0 \cdot 033''$ can be wound on a bobbin, the net winding length of which $= 3''$ and the extreme diameters of winding 1″ and 3″ respectively?

From page 160 we have the total number of turns

$$T = \frac{L \cdot t}{d^2} = \frac{3 \times 1}{(\cdot 033)^2} = \frac{3}{\cdot 001089} = 2755 \text{ turns.}$$

Example 4.—What is the maximum current which can be sent through the above coil in order that its temperature rise may not be greater than 50° C. above that of the air?

The resistance (R) of the coil must first be found; thus

$$R = \frac{l\rho}{A} = \frac{4l\rho}{\pi d^2} \text{ ohms,}$$

and $$l = mT = \pi\left(\frac{D_1 + D_2}{2}\right)T = \pi \cdot \frac{4}{2} \cdot 2755 = 5510\pi \text{ inches,}$$

$$\therefore \quad R = \frac{4 \cdot 5510\pi \times \cdot 00000066788}{\pi \cdot (\cdot 028)^2} = 18 \cdot 73 \text{ ohms,}$$

and the surface of the winding

$$S = \pi D_2 L = \pi 3 \times 3 = 9\pi \text{ square inches.}$$

Hence the maximum current

$$= 0 \cdot 95 \sqrt{\frac{S}{R}} = \sqrt{\frac{9\pi}{18 \cdot 73}} = 1 \cdot 51 \text{ ampere.}$$

QUESTIONS ON CHAPTER V

[*Supplement all Answers with Sketches when possible.*]

1. Find both the magneto-motive force and the magnetising force per unit length acting in a magnetic circuit 30 cms. long, and which is energised by a current of 2 amperes flowing round the 1000 turns surrounding the circuit.

2. In the above question, how many ampere turns would be required to produce a magnetising force (per unit length) of 100 C.G.S. units?

3. Find the number of lines of force produced when a current of 5 amperes flows through 200 turns of wire surrounding a magnetic circuit, the length of which = 25 cms., cross section 15 sq. cms., $\mu = 1000$. Give also the induction-density in the magnetic circuit.

4. If a magnetising force of 50 C.G.S. units produces an induction-density of 16,000 lines per sq. cm. in a magnetic circuit, what is the value of the permeability μ?

5. Find the loss of power due to magnetic hysteresis in a cylinder of soft iron which rotates at a speed of 1200 revolutions per minute between the two poles of an electro-magnet. The volume of iron is 1000 c.c., and the specific magnetic hysteresis 9000 ergs per c.c. per cycle per sec.

6. How many turns of wire, insulated to 0·05" diameter, can be wound on a bobbin, the net winding length of which = 3" and the inner and outer winding diameter ½" and 1½" respectively?

7. Find the total length of wire on the coil in the last question, together with its resistance, if the material is copper, having a diameter bare of 0·04".

8. What must be the diameter of the copper wire on a bobbin so that its resistance may be 5 ohms, if the winding length = 4", winding depth 2", inside diameter ½", thickness of insulation on the wire 15 % on the diameter of the bare wire?

9. In the last question, what is the weight of copper on the coil if copper weighs 555 lbs. per cubic foot?

10. A coil is 6" long, 4" outside diameter, and has a resistance of 5 ohms. Find the maximum permissible current for a rise of temperature of 50° C.

11. Show by means of curves the approximate numerical relations between magnetic induction and permeability for good specimens of cast-iron, wrought-iron, and cast dynamo steel respectively. (Ord. Grade, E.L., C. and G., 1902.)

12. An electro-magnet is required to work quickly and to let go the armature

instantly on the cessation of the current. How could this result be obtained? (Prelim. Grade, C. and G., 1901.)

13. An electro-magnet has to be designed to produce an approximately uniform field of 10,000 lines per sq. cm. over an area of 12 sq. cms. in an air-gap half a cm. long. Sketch an electro-magnet approximately to scale, with which this result can be obtained without undue heating of the coils. State the gauge of wire, number of turns, current, etc., that may be used, and describe in detail how your results are obtained. (Hons. Grade, C. and G., 1900.)

14. What magnetic quantities are denoted by the symbols H, B, and μ, and how are they related to one another? (Ord. Grade, C. and G., 1895.)

15. Calculate the number of ampere turns of excitation required to magnetise up to 14,000 lines per sq. cm. a soft iron ring 20″ in mean diameter, made of round iron 1″ thick. (Assume permeability = 800.) (Ord. Grade, C. and G., 1894.)

16. A closed soft iron ring, 100 cms. mean circumference and 5 sq. cms. cross section, is uniformly wound with 200 turns of insulated wire. Suppose you have found that the following relations exist in iron of this quality—

B =	10,200	12,000	13,700
μ =	2000	1500	1000

Calculate the current (C) at which the total flux of magnetic lines is 65,000 C.G.S. lines. (Ord. Grade, C. and G., 1892.)

17. Calculate the size, resistance, and weight of copper wire such that, if wound on a magnet core 7″ × 3½″, and having a P.D. of 25 volts maintained between the terminals, 5000 ampere turns will be produced. (Length inside 'former' is 8″.) (Ord. 1898.)

18. Calculate the size, resistance, and weight of copper wire such that, if wound on a cylindrical iron core 6″ long, 3½″ diameter, and having a P.D. of 50 volts between its terminals, 4400 ampere turns will be produced. The diameter of the completed coil is to be 7¾″. A cubic foot of copper weighs 550 lbs. (Ord. 1900.)

19. Explain why an electro-magnet with a total resistance of 50 ohms, connected direct to a battery of very low resistance, will be more powerfully magnetised if its two coils are joined up in 'multiple arc,' than would be the case if the coils are joined up in 'series.' Also explain why the reverse is the case if the battery and electro-magnet be in circuit, with a resistance which is very high compared with the resistance of the electro-magnet. (Hons. Teleg. 1900.)

20. How would you calculate the length and diameter of a copper wire required to completely fill a bobbin of a given size to a given total resistance; the thickness of the silk covering of the wire *a* being taken into account, *b* being taken as negligible? (Hons. T. and T. 1901.)

21. What is known by the symbols 'H' and 'B' in electro-magnetics? State what effect the introduction of iron has on the lines of force in a solenoid traversed by a current. (Ord. T. and T. 1901.)

22. Calculate approximately the strength of the magnetic field produced at the centre of a solenoid 4″ long, the coils of which are 1½″ thick and have a mean diameter of 7½″, when the current density taken over wire and insulation together and measured on a plane containing the axis of the solenoid is 750 amperes per sq. in. Could a coil so constructed and working with this current density be used for long periods without undue heating? (Hons. Sect. I. 1901.)

23. The resistance of the wire on a bobbin fully wound with silk-covered wire 7 mils diameter is found to be 120 ohms; what will be the resistance if the same bobbin be equally wound with 10-mil wire? The thickness of covering to be taken as 1 mil in each case, what will be the relative numbers of convolutions in the two cases? (Hons. Teleg. 1902.)

24. How do you picture to yourself the change which occurs in the core of an electro-magnet when the current is turned on? (Prelim. 1904.)

CHAPTER VI

ELECTRO-STATIC AND ELECTRO-MAGNETIC INDUCTION

Electro-static Induction.—In the present chapter the fundamental principles involved in the production of transient or momentary currents of electricity will be considered. The subject is both interesting and of the greatest practical importance, forming as it does the basis of the action of important electrical engineering appliances.

We have already defined the unit of electric quantity called a '*coulomb*' as *the quantity of electricity which flows per second past any point of a conductor carrying one ampere.* It is therefore an easy matter to evaluate the number of coulombs of electricity given to a circuit in a specified time when the current is constant in strength, the measurements required in such cases being that of the time of duration of the flow and the current strength, which latter is easily obtainable.

Measurement of Transient or Induced Currents.—When, however, it is desired to ascertain the charge or quantity of electricity on a charged body, this must be emptied of its charge, so to speak, through some measuring arrangement. A difficulty arises or may arise now, owing to the current produced by the discharge, in the first place, lasting an extremely short time; and, secondly, to its diminishing in strength extremely rapidly during this time of discharge. The effect may be likened to a bucket of water being quickly emptied into a slanting gutter with a drain at the lower end, the rush of water down the drain very rapidly diminishing to a mere trickle. Clearly in this case the measurement of the quantity of water passing the drain would not be correct unless the receptacle employed to catch it was kept there long enough to catch the last drop.

The measurement of electric quantities is obtained by connecting, in the circuit through which the discharge is to take place, the coils of a suitable measuring instrument, arranged so that the whole of the discharge and resulting current passes through before the instrument begins to indicate. In this case the total effect of the rapidly diminishing current of discharge is proportional to the first fling or

deflection of the instrument, and we have therefore a measure of the quantity which has passed. The instrument for effecting the measurement of such transient or momentary currents of rapidly varying strength is termed a '*ballistic galvanometer,*' and the description of a commonly used form will be found on page 209, Chapter VII., on measuring instruments.

Referring to page 29 *et seq.*, it was pointed out that any insulated electrical conductor is able to hold a greater charge or quantity of electricity *for the same potential difference* between it and a similar neighbouring conductor when it is closer to this latter conductor than when farther away from it. Further, it was mentioned that the nature of the intervening space played an important part in determining the magnitude of the charge, other things being the same. The nature or quality of the separating substance in virtue of which this influence takes place across it is termed the '*specific inductive capacity*' of the medium. The Greek letter σ is often employed to denote the magnitude of this specific quality, and the value of σ is given on page 30 for a number of important substances.

Conditions for obtaining Capacity. Condensers.—Now any arrangement of two neighbouring conductors separated by an insulator is called an '*electrical condenser,*' the conductors themselves being termed the two *coatings* of the condenser, while the separating insulator or medium is called the *dielectric.* Any given condenser is capable of holding a certain charge of electricity when subjected to a certain electrical pressure, and the charge or quantity of electricity in coulombs required to be given to one of the coatings of a condenser in order to raise the P.D. between the coatings to 1 volt is called the electro-static capacity, or briefly the *capacity*, of the condenser. The capacity of a condenser depends, amongst other things, on the shape and relative positions of its coatings with regard to one another.

Methods of Building Condensers.—In practice there are two main forms of condensers, namely, (1) the flat plate or sheet form and (2) the concentric cylinders form.

Fig. 78 represents in perspective elevation one complete element of the flat form of condenser, while at the same time indicating a very common method of building such an appliance. It consists of two distinct metallic plates or sheets T and *t*, which need only be of the thinnest material obtainable. For this reason *tinfoil* (often only about 0·0003″ thick) is almost invariably used. These metallic *coatings* are insulated or separated from one another by the *dielectric* or sheet of insulating material I. It is important for the thickness of I to be as uniform and as thin as possible in order that the coatings may be close

together. Though any insulating substance can be used as a dielectric, mica is the best, and is always used in the best condensers, because (a) its specific inductive capacity is high, (b) on account of its natural mechanical rigidity it offers great resistance to rupture—*i.e.* to being pierced—by the passage of a spark across it from T to *t*, (c) it offers special facilities in the production of thin sheets of uniform thickness and considerable size.

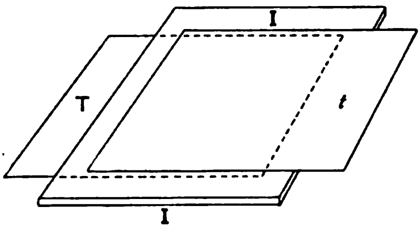


FIG. 78.—Elements of Condenser in Perspective.

The thickness of sheet used in practice varies with the electrical pressure to be employed with the condenser: the greater the latter, the thicker the sheet used. The same thickness is of course used throughout the same condenser, and for ordinary work this may be anything from 0·002″ to 0·008″ thick.

As the specific inductive capacity of any substance is expressed in terms of that of air, which is taken to be unity or 1, it may be represented by the ratio of two quantities in the same units, and is therefore simply a number.

The specific inductive capacity of any dielectric substance is the numeral expressing the ratio of the capacity of any condenser using this substance as dielectric to the capacity of the same condenser using the same thickness of air as dielectric instead.

Referring to the method of building a condenser indicated in Figs. 78 and 79, the sheets of dielectric I may conveniently be made square and the coatings T and *t* *oblong*, but of equal size. The top tinfoil sheet *t* is then placed on I so that I overlaps it by an equal margin (¼″ wide or more) on three sides, *t* overlapping I on the fourth side by any convenient desired amount.

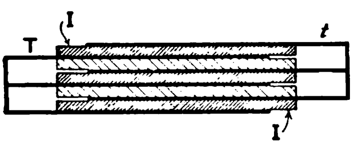


FIG. 79.—Three Sections of Condenser.

The same arrangement is adopted with the other coating T placed on the other face of I, but the overlap of foil T is on the opposite edge of I to that of *t*. The object in having an overlap of the dielectric on three sides and of the foil on opposite edges is to minimise leakage of charge between the coatings, which is fatal to the satisfactory working of any condenser.

Action in a Condenser.—The coatings or terminals of the condenser are therefore T and *t*, and if these are connected to a source of E.M.F. a certain charge or quantity of electricity is imparted to one coating, thereby raising its potential above that of the other coating by

an amount equal to the E.M.F. of the source. A corresponding charge, of opposite sign, is induced by electro-static attraction across I on the opposing face of the other coating (*vide* p. 28). If now the E.M.F. be removed and T, *t* connected together, the two charges combine and neutralise one another, and the condenser is said to be *discharged.*

Another way of viewing the action of a condenser is as follows:— Let T and *t* be connected to the same E.M.F. and be separated by a considerable distance. If *t* is connected to the $+^{ve}$ end of the E.M.F., electricity will flow into *t*, quickly raising its potential to the maximum of the source, while the potential of T and the induced charge on it will be very small. As T approaches *t*, the charge of opposite sign on it, which is induced by *t*, gradually increases, and the potential at *t* due to it tends to diminish the potential of *t* itself, more electricity flowing into *t* in order to maintain its original potential.

A small fraction of a second usually suffices to charge and discharge a condenser, but the quantity discharged is always slightly less than that employed to charge a previously perfectly discharged condenser, owing to a phenomenon met with in all condensers and known as *residual absorption.* This, in a measure, is somewhat analogous to the residual magnetism exhibited in an electro-magnet, or, again, to the temporary set in a wire after torsion, but it is not altogether a happy term. There is no absorption of electricity actually, but apparently it would seem that some small proportion of the original charge remains '*bound*' (*vide* p. 29) after the first discharge, and this may more correctly be termed the *residual charge.* More correctly, this so-called 'residual charge' is due to the gradual recovery of the dielectric from the strain caused by the stress imposed through the force of attraction of the charges of opposite sign on the coatings of the condenser.

Since the 'residual charge' increases with the magnitude of the charge, and also with the time for which the condenser remains charged, and moreover depends on the nature of the substance used as a dielectric, the measurement of capacity by comparison with standards will be complicated when the condensers are built with different kinds of dielectrics. This can be seen from the fact that the capacity will vary with the time of charging with such conditions present. The difficulty in the measurement is got over by methods of comparison, in which the condensers are charged only for an extremely small fraction of a second, and the effects of absorption thereby reduced to a minimum.

There is no absorption in an 'air' condenser, and the phenomenon seems to become more pronounced as the rigidity of dielectric used increases. In papers read before the Hungarian Academy of Science

on May 20, 1901, and June 18, 1900 (*Elektrotechn. Zeitschr.* xxii. pp. 170-215 and 716-785, 1901), M. v. Hoor pointed out that considerable variation occurred in the capacity of a condenser with change of pressure employed in charging it. In paraffined paper condensers and paper-insulated cables the charge increased only about 3 % between 5 and 30 seconds, and at higher P.D.'s only 0·2 %. In glass and megohmit condensers the time required to charge is much increased. The difference between the quantity of charge and discharge was 2 % with paper and megohmit condensers and 6 % with glass. Most of this is got rid of by discharging the condenser a second time.

Another phenomenon met with in *all* condensers which are employed with alternating currents is that known as '*dielectric hysteresis*,' in virtue of which the condenser becomes warm, due to an expenditure of energy in rapidly reversing the sign of the charge with respect to the two coatings. It is analogous to magnetic hysteresis, and cannot be got rid of. It may be minimised by employing a dielectric having a small *specific dielectric hysteresis*, and by using as little of the dielectric as possible. There seems to be the same kind of relationship between residual charge and dielectric hysteresis as there is between residual magnetism and magnetic hysteresis. The same authority (M. v. Hoor) finds that by varying the charging potential in steps a hysteresis curve is obtained which is exactly similar to the ordinary loop curve of magnetic hysteresis (*vide* p. 146). Still more curious is the analogy between the expressions giving the losses of energy due to dielectric hysteresis, which he finds is proportional $e_s^{1\cdot 7}$ (where e_s stands for electro-static induction), and that due to magnetic hysteresis, which we have seen is proportional $B^{1\cdot 6}$.

Now the definition of the capacity of a condenser given on page 168 furnishes us with a very simple relation connecting capacity C, quantity Q, and voltage V.

Suppose that a condenser of capacity C farads is charged and discharged by the application of different pressures V_1, V_2, V_3, . . . volts, and that the quantities of electricity in coulombs flowing into or out of the condenser for these P.D.'s are Q_1, Q_2, Q_3, . . . Then it will be found that

$$C = \frac{Q_1}{V_1} = \frac{Q_2}{V_2} = \frac{Q_3}{V_3} = \text{etc.},$$

which shows us that the capacity of a condenser is always constant. The above rule corresponds with the definition of capacity, and writing it in a more general form we have

$$C = \frac{Q}{V}, \text{ or } Q = CV.$$

Unit of Capacity.—If we make Q = 1 and V = 1 in the above relation, the definition of the practical unit of capacity (called a '*farad*') is obtained; thus, *a farad is the capacity existent in a condenser which requires a* P.D. *of* 1 *volt between its coatings to charge each of them with* 1 *coulomb of electricity.* Such a unit is, however, far too large for practical purposes, and therefore a '*microfarad*' (*i.e.* one-millionth of a farad) is always used to express the value of capacities. Now, referring to Fig. 78, it will be seen that the active or effective area of either metallic coating is equivalent to the area of one face of the dielectric covered by tinfoil *on both sides*—*i.e.* to the whole area of one face of I minus the area of one face of the margin all round.

The final building size of the 'large-type' Swinburne high-pressure condensers for 2000 volts was 20″ × 10″, that of the small-type 10″ × 7½″, while the effective size of coating in each type was a little less than the above dimensions by the margin of dielectric allowed. Owing to the difficulty and expense in obtaining mica in such large sheets the dielectric employed in these condensers is a form of parchmentised paper, known commercially as manilla paper, or commonly as butterskin. This was found to have a specific inductive capacity of 1·86, and when properly dry, six thicknesses (each 0·0011″ thick) broke down and were pierced by 1800 volts roughly. In order to exclude moisture from the dielectric, after the condensers had been baked or dried (paper being hygroscopic), they were immersed in dehydrated paraffin oil contained in suitably sealed receptacles.

In small condensers used with induction coils and such-like, ordinary paper is used for the dielectric, but after first being examined against the light for holes it is soaked in melted paraffin wax to (1) fill up the pores of the paper, and thus make it more homogeneous, (2) make it less hygroscopic, (3) increase its specific inductive capacity. For equal P.D.'s between the coatings a greater thickness of dielectric must be allowed, if prepared paper is used, than if mica is employed, in order to avoid it being pierced by a spark and the condenser breaking down. This is due to the mechanical rigidity of such paper being inferior to that of mica. Owing also to the smaller specific inductive capacity of prepared paper, a condenser made with it would be much more bulky than one using mica for the same capacity and voltage.

Relation between the Capacity of a Condenser and its Dimensions.—In the case of a spherical air-condenser consisting of two concentric spherical metallic surfaces of radii R and r respectively,

separated by air as a dielectric and charged by a source of E.M.F., it can readily be shown [1] that the capacity of such a condenser is

$$C = \frac{Rr}{R - r}.$$

If R and r are nearly equal, *i.e.* if the thickness t of the layer of air between the spheres is very small, we may call R_m the mean radius between R and r, and the last formula becomes

$$C = \frac{R_m^2}{t} \text{ approximately.}$$

But the area A of the surface of a sphere of radius R_m is

$$A = 4\pi R_m^2,$$

and this is approximately the area of the surface of either spherical coating of radius R or r.

Hence substituting the value of

$$R_m^2 = \frac{A}{4\pi}$$

in the previous relation we have the capacity

$$C = \frac{A}{4\pi t} \text{ in electro-static units.}$$

Since the specific inductive capacity σ for air $= 1$, and that for any other dielectric is reckoned in terms of this value for air, and further, since 1 practical unit of capacity (a farad) is equivalent to 9×10^{11} electro-static C.G.S. units, we have a general expression for the capacity of any condenser, namely—

$$C = \frac{A\sigma}{4\pi \,.\, 9 \,.\, 10^{11} t} = \frac{A\sigma}{1 \cdot 13097 \times 10^{13} t} \text{ farads} = \frac{A\sigma}{1 \cdot 13097 \times 10^{7} t} \text{ mfds.},$$

where t is in cms. and A in square cms.;

or $$C = \frac{(2 \cdot 5399)^2 A\sigma}{1 \cdot 13097 \times 10^{13} \times t \times 2 \cdot 5399} = \frac{A\sigma}{4 \cdot 4528 \times 10^{12} t} \text{ farads} = \frac{A\sigma}{4 \cdot 4528 \times 10^{6} t} \text{ mfds.},$$

where t is in inches, A in square inches, and 1 inch $= 2 \cdot 5399$ cms.

The above relations, it must be remembered, are close approximations to the truth in the case of spherical condensers and under the assumptions or conditions named. It can, however, be shown that these relations are also approximately true for condensers of any form, whether flat, cylindrical, or otherwise, providing t is small compared with the linear dimensions of the plates.

We may here with advantage take a few examples of the application of the preceding formulæ :—

[1] The detail of the proof may be found in almost any text-book on electricity and magnetism, space not permitting of it being given here.

Example 1.—What would be the capacity of a condenser consisting of 1000 plates altogether, each $5'' \times 4''$ in effective size, the dielectric being mica $0{\cdot}005''$ thick? Specific inductive capacity of mica to be taken as 5.

Since the dimensions are in inch units, we take the last formula and substitute the values of the symbols, remembering that there will be 500 plates to each coating, and that the effective area of one plate is twice the area of one side.

Hence the capacity

$$C = \frac{A\sigma}{4{\cdot}4528 \times 10^6 t} = \frac{500 \times 2 \times 5 \times 4 \times 5}{4{\cdot}4528 \times 10^6 \times {\cdot}005} = 4{\cdot}49 \text{ mfds.}$$

Example 2.—How many plates altogether will be required for a condenser giving a capacity of 10 mfds., each plate being $10'' \times 8''$ in effective size, the dielectric used being of the same size and material as in Example 1?

The total effective area A of either coating must be found first. Thus

$$A = \frac{4{\cdot}4528 \times 10^6 \times tC}{\sigma} = \frac{4{\cdot}4528 \times 10^6 \times {\cdot}005 \times 10}{5} = 44{,}528 \text{ sq. ins.}$$

The number of plates per coating will therefore be

$$\frac{44528}{2 \times 10 \times 8} = 278{\cdot}3, \text{ say } 279,$$

and the number of plates altogether will be $279 \times 2 = 558$.

Example 3.—If the condenser in Example 1 be charged at a P.D. of 10 volts, what will be the charge?

Since $$Q = CV,$$
the charge will be

$$Q = CV = \frac{4{\cdot}49}{10^6} \times 10 = \frac{44{\cdot}9}{10^6} \text{ coulombs} = 44{\cdot}9 \text{ microcoulombs.}$$

Example 4.—What must be the capacity of a condenser which requires a P.D. of 100 volts to charge it with 10 coulombs?

Here the required capacity

$$C = \frac{Q}{V} = \frac{10}{100} = \frac{1}{10} \text{ farad.}$$

Rules governing Capacity of Condensers.—These are three in number, and may now be enunciated as follows:—

1. The capacity of a condenser is directly proportional to the *effective* area of either of its coatings.

2. The capacity of a condenser with flat parallel plates is inversely proportional to the distance between the plates of the two coatings.

3. The capacity of a condenser is directly proportional to the specific inductive capacity of the dielectric separating the coatings.

The somewhat striking analogy between the foregoing rules and those in connection with the resistance of a conductor (p. 68) is worth noting.

Now bearing in mind the construction shown in Fig. 78, it will be seen that for a given dielectric (*e.g.* the best) a large capacity can only be obtained by having the plates or coatings of a condenser very large or very close together. A limit to both is, however, soon reached—to the former, owing to bulkiness, to the latter, owing to the risk of the dielectric being pierced by the charge. Such an arrangement as shown in Fig. 78 would have a capacity of only a very small fraction of a microfarad; but a large capacity having a convenient size and thickness of dielectric can easily be made by combining a large number of such elements as indicated in side-sectional elevation by Fig. 79, which shows three plates per coating. In this manner a condenser can be made, each coating of which may consist of hundreds of tinfoil sheets connected together as at t or T to form one of the two terminals. The sheets of one coating are interleaved alternately with those of the other coating, and separated from them by the sheets of dielectric. The effective area of each sheet of foil is equal to the sum of its two faces actually covered on each side by the tinfoil sheets of the other coating; or, if β is the effective area of one face of one plate, then the number of plates in each coating $= \frac{A}{2\beta}$.

Fig. 80 shows the general view of a tinfoil and mica condenser in a containing-box the outside dimensions of which are 13″ × 8″ × 14″ deep. It is built up in sections having six separate capacities of 0·5, 0·5, 2, 3, 4, and 10 mfds., respectively, and connected to a special form of plug switchboard on the top, designed by the author for the purpose of enabling the several capacities to be used singly or in any combination series, parallel, or parallel series so as to multiply the number of different values of capacity obtainable. With pure parallel combinations only, any capacity from 1 to 20 mfds., by 1 mfd. at a time, can be obtained.

FIG. 80.—Photo of 20-mfd. Condenser.

The plates of foil and dielectric in all condensers are pressed tightly against one another by suitable clamping plates and rods. A

description of the Kelvin brass plate '*air*' condenser, for use as a standard in measuring the small capacities of short lengths of electric light cables, will be found in *Electrical Engineering Testing*, by the author; its capacity being 0·0025 mfd. To give the reader an idea of the quantities pertaining to a Swinburne high-pressure large-type condenser for use with alternating currents, the following figures are given: For 2000 volts and 7 mfds. capacity, 8000 sheets of butterskin and 666 sheets of tinfoil are employed, the current of charge and discharge at 50 complete cycles of alternation per second being 4·4 amperes. For 500 volts and 100 mfds. capacity, 7500 sheets of butterskin and 2500 sheets of foil are used, the current being 15·71 amperes.

L. Lombardi, in an article on high-tension condensers (*Elettricità*, Milan, 19. Oct. 6, 1900), uses tinfoil sheets and paraffin-wax sheets prepared by a special process, and which are thin and perfectly homogeneous. Sheets 36 × 49 cms. and 1·2 mm. thick were tested at 17,000 volts, and made up into 10 condenser sections of 50 sheets each. The rise of temperature (measured by a thermocouple) of each section after 10 hours at 5000 volts was 1·4° C. at the centre of the sheets and 3·2° C. at the edge. The loss in the whole condenser at 50 cycles per second was 100 watts. A condenser capable of working continuously on 10,000 volts would have a thickness of dielectric = 2 mms., and a 1-mfd. condenser would require a little over 200 lbs. of this dielectric, the total cost of all materials not exceeding £14.

Cylindrical Condensers—Capacity of Electric Mains.—Remembering the principles and definitions already enunciated, we are able to see that any so-called electrical conductor or cable, consisting in its simplest form of a copper or metallic conductor insulated all over with some insulating substance, may possess electro-static capacity. For instance, such a cable lying on the ground has a capacity which depends primarily on its geometrical form, *i.e.* whether it is coiled up or is lying straight, for the copper core and earth form the two coatings which are separated by the insulating covering acting as the dielectric. A submarine telegraph cable possesses capacity to a very much greater degree, and here the water and earth together form the outer coating. The capacity of a single insulated conductor such as that first mentioned is so small that it can be neglected, but that of the so-called concentric cable, a form introduced of recent years, and now used so extensively, is much too large to neglect. As the considerations relating to the effect of capacity in bi-concentric and triple-concentric cables is of great moment to electrical engineers nowadays, we may perhaps profitably consider the expression for the capacity of such a cable.

Let Fig. 81 represent a piece of bi-concentric cable consisting of a central stranded conductor m_1, and an outer stranded one m_2 insulated from the inner by the insulation δ which acts as the dielectric. The outer insulation I takes no part in the production of capacity.

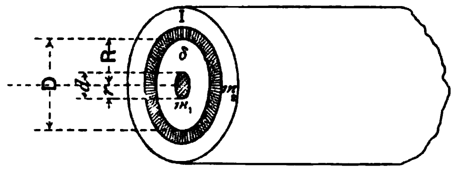


FIG. 81.—Symbolic Sketch of Concentric Cable.

Let R = radius in cms. of the inner surface of the outer main m_2, and r = radius in cms. of the outer surface of the inner main m_1; D and d being the diameters of the surfaces corresponding to the above radii respectively. Let L = length of either conductor or main in cms., and σ = specific inductive capacity of the dielectric δ.

Then it can be shown[1] that the capacity C is given by the standard relation

$$C=\frac{\sigma L}{2\log_e R/r}=\frac{\sigma L}{2\log_e D/d}$$

in electro-static C.G.S. units.

But 1 farad = 9×10^{11} electro-static units of capacity, and

$$2\log_e R/r=2\log_e D/d=2\frac{\log_{10}\text{ratio}}{\log_{10}e}=2\frac{\log_{10}\text{ratio}}{0{\cdot}4343}=4{\cdot}605\log_{10}R/r,$$

where $e = 2{\cdot}71828$ . . . the base of the Napierian—and 10 the base of the ordinary common logarithms.

$$\therefore \qquad C=\frac{\sigma L}{4{\cdot}605\log R/r}\text{C.G.S. units}=\frac{\sigma L}{9\,.\,10^{11}\,.\,4{\cdot}605\log R/r}\text{ farads}$$

$$=\frac{10^6\sigma L}{9\,.\,10^{11}\,.\,4{\cdot}605\log R/r}=\frac{2{\cdot}413}{10^7}\cdot\frac{\sigma L}{\log R/r}\text{ mfds.}$$

But 1 English statute mile = 160,933 cms.

$$\therefore \qquad C=\frac{2{\cdot}413\times 160{,}933}{10^7}\cdot\frac{\sigma}{\log R/r}=\frac{\sigma}{25{\cdot}75\log R/r}\text{ mfds. per mile.}$$

Capacity of Two-Wire Non-concentric Cables.—J. B. Pomey[2] has deduced an expression for the electro-static capacity of a two-core non-concentric cable in which the conductors are parallel.

Thus if σ = the specific inductive capacity of the surrounding insulation, and d = the distance in cms. between the centres of the conductors, whose radii = R_1 and R_2 cms., then the capacity per cm. length of the cable is

$$C=\frac{\sigma}{2\log(K+\sqrt{K^2-1})},$$

[1] Deschanel's *Natural Philosophy—Electricity*, part 3, 1901, p. 62.

[2] *Écl. Électr.* 19. pp. 131-133, 1899.

where $$K = \frac{(d^2 - R_1^2 - R_2^2)}{2R_1R_2}.$$

If the conductors were of equal size, as is most probable, then $R_1 = R_2$

and $$K = \frac{d^2 - 2R_1^2}{2R_1^2}.$$

The capacity of ordinary high-tension bi-concentric electric light cable about 19/18 gauge varies, depending on the maker of it, from about 0·30 to 0·37 mfd. per mile with paper or its compositions as insulation. The same cable having vulcanised rubber insulation instead has about double the above capacity. The capacity of the 'direct Atlantic' telegraph cable between Ireland and Nova Scotia is almost 1000 mfds.

In telegraphing through such a submarine cable, the whole cable has first to be charged, in a similar way to that in which a condenser having a capacity of 1000 mfds. would be charged, before the message is received at the other end; or, in the case of its being tested for insulation resistance, before readings could be taken. This charging of a cable under test for insulation resistance is often termed its '*electrification*,' and is allowed to go on for one minute, in the case of electric light and power cables, before readings are taken on which its insulation resistance is to be calculated. The 'soaking in,' so to speak, of the charge may, and usually does, go on for several minutes (*vide* p. 170), but the greater part occurs in the first minute, and hence this is made a standard time interval and basis of measurement. Since the outer sheathing and water, as we have already remarked, forms one of the coatings of the cable condenser, the copper core being the inner or other coating, we have practically the previous formula for its capacity; or, in the case of an ordinary single-core cable on land or in the sea, we have—

The capacity $$C = \frac{2{\cdot}413 \times 2029 \times 91{\cdot}44}{10^7} \cdot \frac{\sigma L_n}{\log R/r} \text{ mfds.} = \frac{4{\cdot}476}{100} \cdot \frac{\sigma L_n}{\log R/r},$$

where 1 nautical mile (the knot) = (2029 yds. × 91·44 cms. per yd.) cms., L_n = the length of cable in knots, σ = the specific inductive capacity of the insulation used, R and r having the same meaning as before.

In long-distance telephony it is of the utmost importance to neutralise or minimise to the utmost the electro-static capacity and electro-magnetic induction (p. 182 *et seq.*) of the circuit, since telephone currents are rapidly fluctuating ones. The methods of elimination, however, cannot be considered here, but a few particulars of one prominent telephone line, '*the London and Paris*,' will be instructive. There are four conductors side by side, forming two complete outward and return circuits. The lengths of each of the four conductors are—283·5 miles

of overhead, 23 of submarine, and 4·8 underground. The total resistance is 693 ohms, and the capacity 10·62 mfds., of which only 4·05 mfds. is due to the overhead portion. The capacity of the Irish telephone cable is 0·3045 mfd. per knot, the insulation being gutta-percha.

We may here consider a numerical example of the above relations.

Example.—Find the capacity of 2 miles of bi-concentric electric light cable, insulated with vulcanised india-rubber (specific inductive capacity 3·0), if the diameter of the inner surface of the outer main be 1″ and that of the outer surface of the inner main ½″.

Hence

$$C=\frac{2\cdot413}{10^7}\cdot\frac{\sigma L}{\log D/d}=\frac{2\cdot413\times3\times2\times160{,}933}{10^7\times\log 1/\frac{1}{2}}=\frac{14\cdot478\times160{,}933}{10^7\times\cdot301}=0\cdot773\text{ mfd.}$$

where 1 mile $=160{,}933$ cms.

Consequently the above cable has an electro-static capacity of $\frac{0\cdot773}{2}=0\cdot3865$ mfd. per mile.

Energy expended and Work done in Charging and Discharging a Condenser.—If a charge Q of electricity (in coulombs), at a constant or steady pressure, raises the P.D. between the two coatings of a condenser from 0 to V volts, the average P.D. during charge $=\frac{1}{2}V$, and the total work done in charging, or the energy stored up by the condenser, will be $\frac{1}{2}$ QV joules $=\frac{0\cdot7373}{2}$ QV ft.-lbs. $=\frac{QV}{2\cdot712}$ ft.-lbs. But the law of the conservation of energy tells us that the work done in charging a condenser equals that which could be done by the same quantity of electricity on discharge. Hence the above relations give the energy of discharge as well as that of the charge.

Since $$Q=CV,$$

∴ the energy expended by the condenser in discharging is

$$=\frac{QV}{2\cdot712}=\frac{CV^2}{2\cdot712}=\frac{Q^2}{2\cdot712C}\text{ ft.-lbs.}=\frac{1\cdot356\times10^7CV^2}{2\cdot712}\text{ ergs,}$$

where C is the capacity in farads.

The foregoing reasoning shows us that if a condenser is charged from a constant P.D., the energy stored up by the condenser, namely $\frac{1}{2}$(0·7373 QV) ft.-lbs., is half the total taken from the supply, namely (0·7373 QV) ft.-lbs., which latter is partly stored and partly dissipated in charging.

Combinations of Capacities.—Condensers may, like resistances (*vide* p. 83), be connected up in circuit in three distinctive combinations, viz. (1) all in series, (2) all in parallel, (3) partly in series and partly in parallel. Figs. 82-85 indicate four such combinations out of several possible, when, say, four different capacities or con-

densers are employed. Each condenser is represented in the usual way, for simplicity, by two equally long, dark, and parallel lines. The capacities of the four condensers may be termed C_1, C_2, C_3, C_4 respectively, and the terminals of the combination in each case T, T.

Capacities in Series.—If all are in simple '*series*,' or joined '*end on*' to one another, as indicated in Fig. 82, the effect is equivalent to that due to an increase in the thickness of dielectric for the same area of coating. Hence from the relations on page 174 it follows that the capacity C of the combination between T, T will be less than that of any of the individual capacities, and it can be shown that

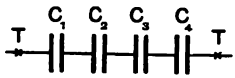


FIG. 82.—Capacities in Series.

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4},$$

or generally
$$C=\frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4}+\ldots+\frac{1}{C_n}},$$

where there are any number (n) of capacities in series. It will therefore be observed that *capacities in series add up or combine like resistances in parallel* (*vide* p. 84). Capacities in series are often spoken of as being in 'cascade.'

Capacities in Parallel.—If all are in 'parallel,' or side by side between the terminals T, T, the arrangement is obviously equivalent to building up or adding together a number of sections, such as that of Fig. 78, to form such as that in Fig. 79; in other words, to enlarging the area of the coatings for the same thickness of dielectric. Thus it follows (p. 174) that the capacity (C) of the combination of condensers in parallel between T, T will be the sum of the individual capacities.

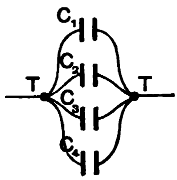


FIG. 83.—Capacities in Parallel.

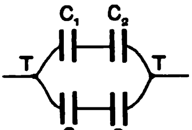


FIG. 84.—Capacities in Parallel Series.

$\therefore$ $$C=C_1+C_2+C_3+C_4,$$

or generally $$C=C_1+C_2+\ldots+C_n,$$

where there are any number (n) of capacities in parallel. It is therefore seen (*vide* p. 84) that *capacities in parallel combine like resistances in series.*

Capacities in Series-Parallel Arrangements.—All other methods of connecting condensers than the above are merely combinations of these two methods. Thus Fig. 84 shows two in series and two in parallel, and from the above rules the combined capacity between T, T is

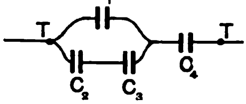


FIG. 85.—Capacities in Series Parallel.

$$C=\left(\frac{1}{\frac{1}{C_1}+\frac{1}{C_2}}\right)+\left(\frac{1}{\frac{1}{C_3}+\frac{1}{C_4}}\right)=\frac{C_1C_2}{C_1+C_2}+\frac{C_3C_4}{C_3+C_4}.$$

Fig. 85 shows yet another arrangement, for which

$$C=\frac{1}{\left(\frac{1}{C_1+\frac{1}{\frac{1}{C_2}+\frac{1}{C_3}}}\right)+\frac{1}{C_4}}.$$

Referring to Fig. 80, it will be seen that the plug switchboard on the top will enable several different combinations, such as those above, to be readily obtained.

Uses of Condensers.—The value or importance of the condenser, and its action in the many uses to which it is put in electrical engineering work, can hardly be over-estimated, and the author desires this to be the excuse for dealing with it more in detail than is customary in most text-books. There are several instances where electro-static capacity occurs through natural causes, in which it acts in a deleterious way. In other cases it may be applied artificially with the greatest utility. As an example, the heavy capacity possessed by a submarine telegraph cable (*vide* p. 178) tends to seriously diminish both the speed of signalling and the economical working of the cable system. In such a case the battery has to charge the cable, which takes some seconds before any effect is produced on the receiving instruments at the distant end. Several devices are resorted to in order to minimise capacity effects in such cables, such as balancing the capacity with an artificial capacity of the same value, as in 'duplex' signalling.

Incidentally, it may be mentioned that the Atlantic cable is so balanced by a condenser containing something like 100,000 square feet of tinfoil. Condensers are used on some land telegraph lines for avoiding 'earth currents'; and again, condensers shunted by a resistance are connected in series with the electro-magnets of instruments to nullify effects of electro-magnetic induction in the coils of certain instruments, so as to increase the speed of signalling; also with certain types of electro-motors known as induction motors. With what are known as electro-static voltmeters (p. 237) three very small capacity condensers are joined in series, and the ends of the extreme combination connected to the very high voltage to be measured. The ordinary electro-static voltmeter is connected to the terminals of one of the three condensers, and hence reads a certain fraction of the total pressure.

The Allgemeine Electric Company use micanite as the dielectric

in the condensers, and by the above device can make an instrument for 7500 volts read on a 25,000-volt circuit. Messrs. Siemens and Halske use porcelain plates 5 mm. thick for the dielectric, and 25 square cms. in area, with coatings of the same area. Condensers are also used with induction coils to increase the spark at the secondary coil and minimise that at the 'contact-breaker' and its destructive effect; with electro-static 'frictional' and 'influence' machines, to increase the length of spark, but for this purpose they take the form known as the '*Leyden jar*,' which consists of a wide-mouthed glass jar coated inside and out—both bottom and sides—with tinfoil up to about $\frac{5}{6}$ths of its height. A metal knob, carried by a metal rod which just passes (without touching) through an insulating cork, is let into a metal foot that rests on bottom of the jar and makes contact with the inner coating. The glass jar is the dielectric and the outer coating the tinfoil outside. These so-called 'Leyden jars' are cylindrical condensers for very large P.D.'s, usually hundreds of thousands of volts at least; and though their capacity is very small, the charge which they can contain may be considerable for

$$Q = CV.$$

Lastly, the effects and uses of condensers with alternating currents are many, and the former in some cases astonishing. Such, however, can more aptly be considered in a later chapter, after alternating currents have been dealt with to some extent. There are many methods of measuring electro-static capacity, but space will not permit of them being considered here. For a detailed description of such methods, together with the apparatus needed and mode of coupling it up, etc., *vide* the laboratory text-book, *Practical Electrical Testing*, by the author.

Electro-magnetic Induction.—By this the reader is to understand the phenomenon of an E.M.F. being set up or created by the *relative motions* of a magnetic field and an electrical conductor. He must be careful not to confuse what is meant in the above statement with that in the action of a coil of wire (carrying current) on a piece of soft iron in the vicinity. In this latter case the coil magnetises the soft iron inductively by inducing a south pole in the end nearest the north pole of the coil. The action, in other words, is magnetisation by induction (*vide* p. 8), whereas the following pages will deal with transient or momentary induced E.M.F.'s in a conductor caused by corresponding alterations in the amount of linkage of lines of force with the conductor. The phenomenon of electro-magnetic induction will be much more readily grasped if the conditions under which it takes place are thoroughly understood.

Induction dependent on Change of Linkage.—As was pointed out in Chapter I., lines of magnetic force are always taken to be continuous or closed loops or paths which run partly in air and partly in any magnetic material in the vicinity. If such a loop of magnetic force encircles part of an electrical conductor, also forming a closed circuit on itself, the two are said to be linked with one another as any two succeeding links of a chain would be. If two magnetic lines of force encircled the same conductor, the linkage of lines and turn would be 2×1, or 2, *i.e.* double the linkage in the previous case.

Further, if these two lines encircled two turns or loops of the conductor instead of only one, the linkage would be 2×2, or 4. Generally, therefore, whenever N lines of force or loops of magnetic induction encircle any point of a conductor looped into T turns, or, which is the same thing, when they pass through the plane or planes of such a looped conductor, the total linkage of lines of force and turns is TN linkages.

We may now state *the one condition* under which it is possible at all for a transient E.M.F. to be set up in a conductor which is situated in a magnetic field, namely, that *there must be relative motion of field and conductor in such a way as to cause the linkage between them to actually change in amount.* To cite a definite instance, imagine a circular conductor in the form of a hoop placed in a *uniform* magnetic field (*i.e.* a field in which the lines of force are straight, parallel, and equidistant from one another) with its plane perpendicular to the direction of the lines of force. Now, *no E.M.F.* will be induced in the hoop if it moves either way in a direction parallel to the lines of force or perpendicular to them. The former motion is one of slipping along only, and no cutting occurs at all; the latter motion of cutting only, but the two halves of the hoop cut the field in the same sense, thereby giving rise to two *equal* E.M.F.'s in opposite directions round the hoop, which neutralise, so that no induced E.M.F. is *observable.*

In both motions it is obvious that the hoop encloses exactly the same number of lines of force in all positions, hence the amount of linkage is unchanged, and therefore there is no induced E.M.F. An E.M.F. will, however, be induced if the hoop moves in a non-uniform field in any way such that it cuts across while enclosing some of the field, because in such a motion the linkage is continually changing in magnitude. If the plane of the hoop is tilted as it moves across the lines of force an E.M.F. *will* be induced in it, for then one-half will cut the lines at a different rate to the other half, thus creating two *unequal* but opposite E.M.F.'s. The difference between these

E.M.F.'s is the effective E.M.F., while its production, in other words, has been caused through an *alteration of linkage* during motion. The foregoing actions would occur precisely if the magnetic field moved instead of the hoop, or if both moved.

Induction between Parallel Straight Conductors.—On page 122 we saw that any conductor carrying current was surrounded by a magnetic field consisting of circular lines of force concentric with the conductor. Further, that if the rest of the circuit was close enough to the portion under consideration, this field was distorted somewhat into an eccentric, non-circular form round the conductor.

Let Fig. 86 represent an arrangement of two conductors PP_1 and SS_1 side by side, and forming portions of two complete but distinct circuits. G is a ballistic galvanometer (p. 209) in circuit with SS_1, while B is a source of E.M.F. and K a key in circuit together with PP_1. On closing K, thus completing the circuit through B and PP_1, a current is sent through PP_1 by the E.M.F. B in the direction of the arrow, *i.e.* from P to P_1. The whole circuit PP_1BKP is therefore completely enveloped in a magnetic field; but restricting our attention to the lines of force F in a single plane through one point in PP_1, we see that these lines in springing out, at the moment of closing K, cut the conductor SS_1. A sudden momentary deflection of G is observable, indicating the presence of a momentary E.M.F., and therefore of current in the circuit of SS_1. On breaking circuit at K, the lines of force collapse in disappearing, due to stoppage of current, and therefore cut SS_1 on the opposite side. This causes an E.M.F. and current to be induced in SS_1 in the opposite direction to that on closing K, as indicated by G deflecting in the opposite direction.

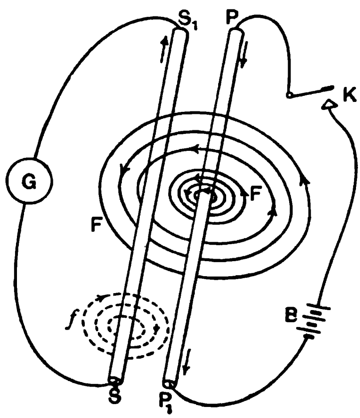


FIG. 86.—Induced Currents in two Parallel Conductors.

Further, since we have already remarked that it is quite immaterial whether the magnetic field or conductor or both move, it follows, by reasoning, which can also be experimentally verified, that the deflection of G, and therefore the induced E.M.F. and current in SS_1, is in the same direction, no matter whether PP_1 and S_1S are stationary and K is made, or the current in PP_1 is steady, and SS_1 is suddenly moved sideways *towards* it. The converse is also true, namely, the induced E.M.F. and current in SS_1 is set up in the opposite direction to that

just named if PP_1 and SS_1 are stationary and K is opened, or if the current in PP_1 is steady and SS_1 suddenly moved sideways *away* from it. These effects, it will be observed, occur *only* within the interval during which the motion of the conductor or the closing and opening of K takes place, and they are due to the sudden alteration in the linkage between SS_1 and the field of PP_1. It may be observed that currents would also be set up in S_1S in opposite directions by keeping SS_1 fixed and moving PP_1 towards or away from it respectively while K is closed.

Determination of Direction of an Induced Current.—We may now digress for a moment in order to give a rule for finding the direction of the induced current. The prediction of the direction is a most important matter, and the following rule, due to Professor J. A. Fleming, is one of the simplest and most easily applied, and should be remembered :—

Set the thumb and two first fingers of the right hand to point in three directions at right angles to one another. Then if the hand be placed so that the thumb points in the direction of motion and the first finger in the direction of the lines of force, then the second finger will point in the direction of the induced E.M.F.

Applying this rule to Fig. 86, we find that on closing K the induced current flows from S to S_1, *i.e.* in exactly the opposite sense to that of the current flowing from P to P_1 which produces it.

Induction between a Magnet and Coiled Circuits.—We may now go a step further and imagine that the wire SS_1 of Fig. 86 *has* been long enough to form a coil or solenoid C (Fig. 87) having a hollow interior for convenience. The ends of C are joined as before by a sensitive ballistic galvanometer G, and M is a permanent steel magnet which can be inserted into the interior of the hollow solenoid C. Now on making, first of all, the south pole S approach C and reach the right-hand end by a succession of steps, a succession of corresponding E.M.F.'s will be induced in C, causing currents to flow which will all be in the same direction as indicated on G. Conversely, if M be withdrawn in steps to the position shown in Fig. 87, a succession of induced currents will flow through G in the opposite direction.

Some writers term the induced currents set up by the approach of M '*inverse currents*,' those set up by the removal of M '*direct currents*'; but such terms have little to commend them, since they do not even characterise the action going on in any way. More appropriate terms would undoubtedly be '*demagnetising*' and '*magnetising*' currents respectively; for these express not only the action of the induced currents on what is causing them, but also their relative directions of

flow. In this latter case it is quite obvious from first principles (*vide* p. 126) that a current which can demagnetise and create magnetisation in the reverse sense must flow in exactly the opposite direction to that which magnetises. We shall therefore employ the latter appellations whenever they may be needed in the future. The insertion of M (S pole foremost) will induce a current in the same direction in C and G as withdrawing M (S pole foremost) from the same end of the coil, and *vice versa.* Further, the same actions will take place if the coil C be moved instead of the magnet M, or if both are moved simultaneously. *An E.M.F. will, however, be induced only during the period of motion*, and will cease to exist immediately the motion ceases.

Induction between Coiled Circuits.—Next imagine that the conductor PP_1 of Fig. 86 is long enough to be wound in the form of a

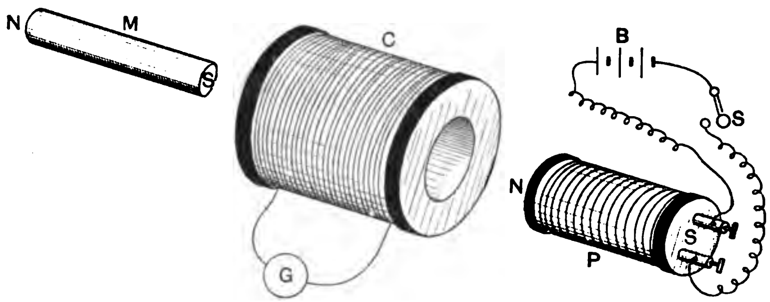


FIG. 87.—Magnet and Telescopic Coils, etc.

solenoid or coil P (Fig. 87) of such a diameter as to be capable of being easily slipped through the hollow interior of the coil C. Let the ends of the coil P be brought to two terminals, seen at the end of the bobbin on which it is wound, and which are connected to a switch S and E.M.F. B by fairly long connecting wires. Now if S is closed, and a current sent from B through P, the whole coil P becomes practically a bar magnet, and all the preceding effects obtained with M and C can be exactly reproduced with P and C.

There are, however, several additional effects which were not obtainable with M. For instance, on closing S with P and C, as shown in Fig. 87, a transient E.M.F. will be induced and a demagnetising current will flow in C, and this will be in the same direction which it would take if P is next made to suddenly approach C. Reversing these operations will produce exactly the reverse effects. Further, inserting P (N pole foremost) into one end of C will set up induced currents in C in the same direction as inserting M (S pole foremost) into the other end of C, the converse operation producing exactly the reverse effect.

Again, if P is inside C, then E.M.F.'s in opposite directions will be induced in C on closing and opening S. In all cases the currents set up by the induced E.M.F.'s are transient or momentary, and occur only at the moment of the make and break of current in P, or during the motion of the latter, or C, or both. The case of P being inside C is an extremely important one from a practical point of view, representing as it does the main principle of important appliances known as the *induction coil*, which is used with direct current, and the *static transformer*, used with alternating current. The arrange-

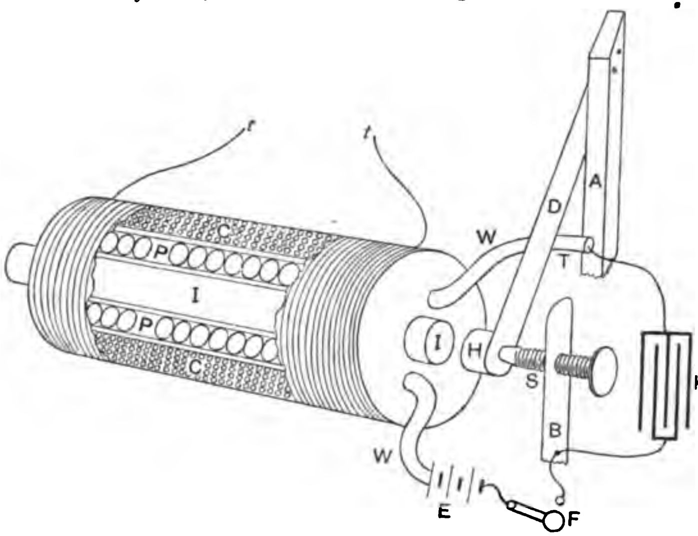


FIG. 88.—Diagrammatic Sketch of the Principle of a Spark Coil.

ment, with slight modification, is also employed in important magnetic measurements.

Ruhmkorff Induction or Spark Coil.—Such an arrangement at once leads us to the so-called *Ruhmkorff's induction coil*, or *spark coil*, as it is now often termed. Seeing the many uses to which this appliance is put, of which perhaps the most important is that in *wireless telegraphy*, it will not be out of place to give a general description of the principles of construction and action. The object of such an appliance is to obtain induced currents at high P.D.'s (or of great *intensity*, as it is commonly termed) at the secondary coil terminals, from stronger intermittent currents at a low P.D. in the primary coil.

A diagrammatic sketch of the induction coil is shown in Fig. 88. It consists of a tolerably short length of insulated thick copper wire wound into a coil of comparatively few turns, which constitute the primary or magnetising coil P.

This primary coil P encircles a soft iron core I, consisting of a bundle of small, soft iron wires, the function of which is to increase the induction due to P, and with it the linkage of this induction with the secondary coil. It is built up with small wires (*i.e.* laminated) in order to avoid the induced or eddy currents, which, if it was a solid bar, would be set up in its cross section, and would retard the rapidity of growth and decay of primary current. The coil P is made with a few thick turns in order to have a small resistance and self-induction (*vide* p. 194). The secondary coil C, which is wound over P, consists of a very long length of insulated thin copper wire wound into a coil of a very large number of turns, so as to produce a large linkage of its turns with the field created by P; the greater the number of turns the greater the induced E.M.F. of this secondary coil C between its ends *t*, *t*. The end of the core I when magnetised is capable of attracting a soft iron head H fixed to the end of a horizontal piece of spring strip D, which is in turn supported on a fixed pillar A. When unattracted HD springs back against an adjustable screw S carried on a fixed pillar B. The ends W of the primary coil P are connected, the one to the pillar A, the other to one terminal of the source of E.M.F. E, which is to work the coil. The other end of E is connected to the pillar B through a make and break switch F, and a condenser K (*vide* p. 168 *et seq.*), made usually of tinfoil and paraffined paper, is connected in circuit across the pillars A and B. In Fig. 88 only a simple make and break key F is shown in place of the usual reversing switch.

Action of Induction Coil.—When F is closed, E sends a current through P which magnetises the core I. The hammer H is simultaneously attracted to I, and, in the act, breaks contact with S, thereby cutting off the current in P. The instant this happens, H ceases to be attracted by I, and springs back on to S, making contact, and again causing the primary current to circulate in P, when the whole previous action is repeated. In this way the current from F through P is very rapidly made and broken alternately, and the core I thereby magnetised and demagnetised alternately. By the action mentioned on p. 196, however, a destructive spark occurs between H and S when H is attracted to I, *i.e.* when the circuit of P is broken. This and its effect is minimised in two ways—(1) by tipping the points of contact of S and H with platinum, which, being a highly inoxidisable material, always remains clean, and is not burnt by the spark, so that good contact is always made; (2) by the insertion of the condenser K across A and B, *i.e.* literally across H and S, which is technically termed the '*contact breaker*,' or '*circuit breaker*.' The *action of the condenser* is as

follows :—On closing F, or this being closed, whenever H touches S, K is discharged, but when the break between H and S occurs the extra self-induced current (p. 196), due to the self-induction of P, having to charge K, is unable to spark across HS, and the current is broken very quickly. Now before the next '*make*' of H and S the condenser K discharges through P in the opposite direction to that in which it would have gone if it had been able to discharge across HS, *i.e.* in the direction opposite to that of the primary current from E. The object, therefore, of the condenser is to cause the 'break' in the current to be more rapid by reducing the spark at HS, and, further, to store up the energy of the self-induced primary current so that the effect of the

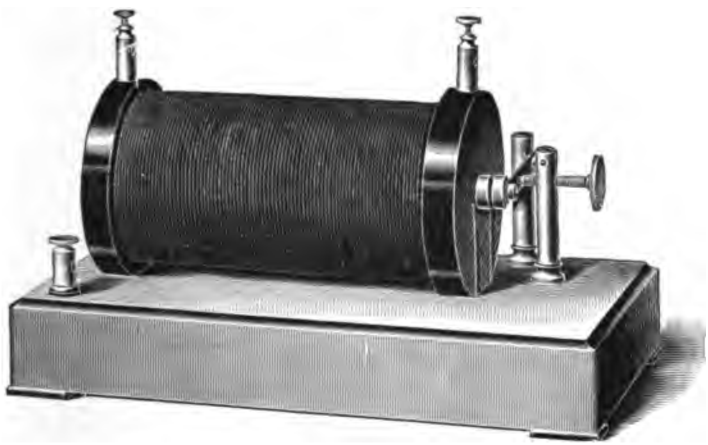


FIG. 89.—General View of Induction Coil.

induced (demagnetising) current in the secondary, set up when the primary circuit is made, is minimised. The E.M.F. of the secondary is thus considerably increased, while injurious effects in the working of the induction coil are minimised. The general view of an induction coil having a condenser in the base is shown in Fig. 89, and is supplied by the General Electric Company. P. Dubois, in a discussion on 'Condensers for Induction Coils,'[1] points out that the utility of a condenser in increasing the secondary E.M.F. in an induction coil ceases when the capacity exceeds a certain limit. The author's determination of the best proportion of capacity and secondary coil resistance is from 3 mfds. for 225 ohms to 0·2 mfd. for 5225 ohms. He finds that 10 mfds. stop all physiological action of the secondary coil. T. Mizuno, in a paper[2] on 'Condensers in Induction Coils,' points out that there is

[1] *Annal. Phys. Chem.* 65. i. p. 86, 1898. *Vide* paper on 'Induction Coils' by H. Armaguat (*Écl. Électr.* 15. pp. 52-62, 1898).

[2] *Phil. Mag.* 45. pp. 447-454, 1898.

a special magnitude of capacity required for each value of primary current in order to produce maximum secondary spark-lengths, and it is greater the stronger that current. Further, that each turn is completely enveloped by its own lines of force throughout its entire length when a current flows through it; but for clearness we are only considering the actions in a plane passing at right angles through the points so chosen.

Laws of Electro-magnetic Induction.—We may now with advantage collect the facts mentioned in the foregoing pages, and state them in the form of rules as follows:—

1. A transient or momentary E.M.F. will be induced in any conductor (coiled or otherwise, and forming part of a closed or open circuit) if the linkage of the conductor with any magnetic field changes. This transient E.M.F. will set up a corresponding transient current if the circuit of the conductor be closed.

2. The induced E.M.F. and current only lasts as long as the change in the amount of linkage lasts.

3. An increase in the number of lines of force passing through a circuit, *i.e.* an increase in the linkage between the circuit and magnetic field, sets up a demagnetising current, while a decrease of such linkage produces a magnetising current.

4. By Lenz's Law the induced currents have such a direction that they tend to oppose and retard the motion or currents producing them. For instance, the currents induced in C by the approach of either M or P towards C, tend to stop such motion, and at the same time tend to demagnetise both M and P. The principle enunciated in this rule is of extreme practical importance, and should be remembered.

5. The magnitude of the E.M.F. induced in a conductor is measured by the *rate of change* (whether increase or decrease) in the linkage of lines of force with it. Thus the quicker the motion of M or C, or the more rapid the make and break at the switch S, the greater will be the induced E.M.F.

6. The magnitude of the E.M.F. induced is proportional to the linkage of lines of force and turns of conductor; the greater each of these is, the greater will be the E.M.F. for the same rate of change of linkage.

Evaluation of Induced E.M.F.—Now we may express the magnitude of an induced E.M.F. and current as follows:—Suppose the number of lines of force linked with a circuit changes from a value N_1 to a value N_2 in a very short interval of time t. Then the change in linkage $= N_1 - N_2$, and the average rate of change in linkage

$E = \frac{N_1 - N_2}{t}$, *i.e.* the numerical value of the average E.M.F., E induced (by Faraday's Law).

In mathematical parlance the comparatively small change $N_1 - N_2$ is usually written dN, and the small interval of time (t) in which this occurs is written dt. Consequently if in a short interval of time dt second, dN lines of force are cut by the circuit.

Then the average E.M.F. induced during the interval is—

$$E = \pm \frac{dN}{dt},$$

since 1 C.G.S. unit of E.M.F. is set up when a conductor cuts 1 C.G.S. line of force per second, and 1 volt $= 10^8$ C.G.S. units,

$$\therefore \qquad E = \pm \frac{dN}{10^8 dt} \text{ volts.}$$

But $$C = \frac{E}{R}$$

by Ohm's Law, where C is the induced current, and R the resistance of the circuit through which it flows;

$$\therefore \qquad C = \frac{E}{R} = \frac{N_1 - N_2}{Rt} = \pm \frac{1}{R} \cdot \frac{dN}{dt}.$$

If the linkage of lines of force with the circuit increases, N_2 will be greater than N_1, and $N_1 - N_2$ will be $-^{ve}$.

Hence both E and C will also be negative, meaning that the current is a *demagnetising* one.

Quantity of Electricity in a Transient Current.—If we suppose, for the sake of argument, that the linkage decreases, the $+^{ve}$ sign will be used in the last equation, or

$$C = \frac{1}{R} \cdot \frac{dN}{dt},$$

where $Cdt = \frac{dN}{R}$ = the quantity of electricity flowing through the circuit or set up in the transient current in the time dt.

This extremely important result may be otherwise stated as follows:—If the number of lines of force passing through a circuit of T turns changes by an amount dN in a small interval of time dt, then the whole quantity of electricity set up in the transient current induced is—

$$Q = Cdt = \frac{TdN}{10^8 R} \text{ coulombs.}$$

Referring to Fig. 87, P is called the *primary* coil, while C is termed the *secondary* coil. If C encloses P, and a steady current is flowing through the latter, no induced E.M.F. will be set up in C unless P is moved. With such an arrangement of coils a sudden increase of

current in P will induce demagnetising currents in C. If P had a hollow interior, the insertion of a piece of iron into it would enormously intensify the effects on page 186, due to an enormous increase in the magnetic field produced by P for the same current flowing in it. If with this latter arrangement, namely, P inside C, and an iron core inside P, a metal tube is slipped either (*a*) between the core and primary coil P, or (*b*) between P and the secondary coil C, then the intensity of the shock due to C when the main current is started or stopped in P is reduced. The thicker the tube and the greater its conductivity, the more effective it is in preventing the inductive action of P or C.

In (*a*) above an induced E.M.F. and current is set up in the cross section of the tube which is demagnetising in its effect on the core, hence the effective flux in the core, and therefore the linkage of this flux with the secondary turns of C is reduced. Consequently the same rate of change in this diminished linkage gives a diminished secondary E.M.F., and therefore lessens the spark. In (*b*) above the tube virtually acts as a *magnetic screen*, the induced currents in it causing a diminution of linkage between the secondary and field with a like result. The reader should not forget the origin of the induced current. In producing the relative motion of one circuit, such as P, Fig. 87, with regard to C, work has to be done against the force of attraction or repulsion between the coils. This work has its equivalent, and represents the energy necessary for setting up the induced E.M.F.'s in the secondary C.

Eddy Currents.—It may be well to note here another important form of electro-magnetic induction of a less well-defined nature than what has been considered so far, an explanation of which was first suggested by Faraday and others.

Referring to Fig. 90, suppose a metallic disc D of, say, copper, mounted on a spindle G, to be capable of being rotated by the handle *h*, through the narrow air-gap between the poles NS of a magnet M. Then it is found that not only is the motion of D resisted by some invisible force, but also that the disc becomes warm after a time. These phenomena were shown by Faraday to be due to electric currents induced by the relative motion of D and M in the disc, and which reacted on the fixed magnet in such a way as to tend to stop the motion which produced them. In fact, the induced current flows radially inwards or outwards, depending on the direction of rotation, and he showed that it can be led through an external circuit C by connecting the latter to two spring strips or bushes E and F pressing on the spindle G and rim of D respectively as it rotates. For the position of M and direction of rotation of D shown, the induced

current flows from centre to circumference as indicated at CC, and reverses with a reversal of the direction of rotation.

The maximum induced E.M.F. acts in a radial line between the poles N and S perpendicular to the direction of motion, and if the circuit C is open the currents set up in D assume the form of little whirls or *eddy currents* A and B in the disc D. As will be seen, A repels and B attracts the poles (p. 4), both having a common direction along the radius, and an effect, as set forth in *Lenz's* Law. Radial slits in D will obviously reduce the retarding effect of such currents, and, again, the greater the conductivity of D the greater will be the retarding effect, owing to the increased strength of the currents induced, which after all obey *Ohm's* Law, *e.g.* a copper disc will be much more retarded than an iron one of the same size for the same magnet M, owing to the latter having a higher resistance than the former. Thus, when the disc is spun in a magnetic field as shown, the energy spent in driving it is first converted into the energy of the *eddy* or *Foucault* currents, as they are often termed, and is then transformed into heat. Further, it will be seen that for a given magnet and disc the induced E.M.F. and current, and therefore the retarding effect, will be proportional to the speed of rotation.

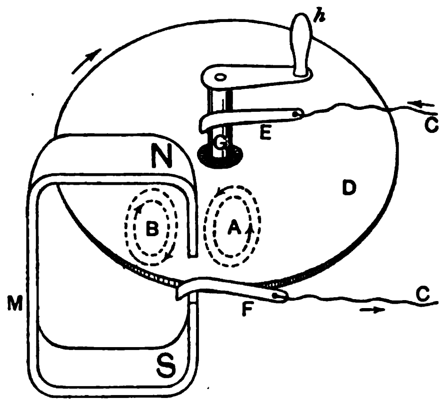


FIG. 90.—Eddies in Disc.

Fig. 91 indicates another instance of the production of eddy currents, in which a metallic frame ABCD is capable of swinging to and fro about an axis WW, between the poles of a magnet NS. If the frame be turned in the direction shown, by the rule on page 185, we see that currents will be induced in the limbs AD and BC in directions from D to A and from B to C respectively. These currents, it will be noticed, coincide in direction, and will by Lenz's Law retard the motion. In addition, eddy currents E will be induced in the sides AD and BC in such a sense as to also retard the motion. Thus the movements of the frame will be well damped and made highly aperiodic.

Figs. 90 and 91 indicate the principle of arrangements employed to an enormous extent in practical electrical engineering appliances and other work. While, however, eddy currents are capable of a

most useful employment in some cases, they must be eliminated or minimised in others, *e.g.* in dynamo-electric machinery, where they exercise a demagnetising and injurious effect.

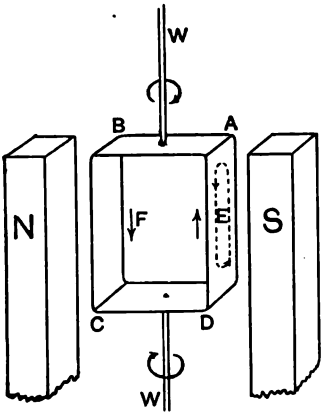


FIG. 91.—Eddies in D'Arsonval Frame.

Self-Induction.—We have seen how an E.M.F. is induced in the conductor SS_1 (Fig. 86) when a current is started, stopped, or varied in the neighbouring conductor PP_1, and also when one or other or both of the conductors are moved, with a steady current flowing in PP_1. Now this would have been the case also had PP_1 and SS_1 formed two different portions of the same circuit. In order to see this more clearly, let a conductor C be wound into the form of a coil or spiral of, say, four turns 1, 2, 3, and 4, as shown in Fig. 92. Let the ends of the spiral be connected to some source of E.M.F. capable of sending a current in a clockwise direction round the spiral from + to –. Now, for the sake of clearness, we will merely consider the action taking place at some point in each of the turns 1, 2, and 3, for the reader must remember that *the same action occurs at every other point in these turns all the way round.*

Now if the current is suddenly *made* or *increased* in C, lines of force represented by the thin elliptical lines F_2 will suddenly be created in concentric figures around every point in turn 2 (also, of course, around every other turn), the direction being as shown by the arrowheads on F_2. These lines of force, in springing out, cut all the neighbouring turns 1, 3, . . ., etc., and in so doing it is quite evident from previous reasoning that they will set up E.M.F.'s in these turns 1, 3, . . ., etc. By applying the rule on page 185 it is seen at once that these induced momentary E.M.F.'s act in exactly the opposite direction to that sending the current through C, and the resulting

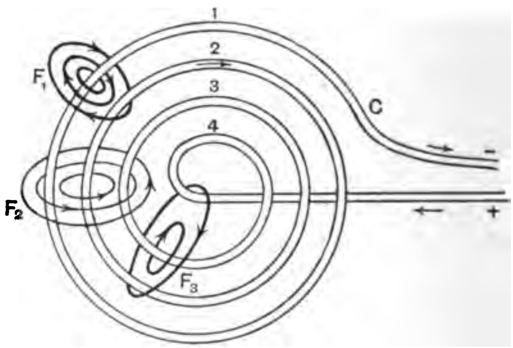


FIG. 92.—Hair-Spring Spiral showing Self-Induction.

currents in 1, 2, . . ., etc. will set up lines of force F_1, F_3, . . ., etc. of their own, therefore, in a direction exactly opposite to F_2 as indicated. Consequently these lines of force F_1, F_3, . . ., etc. in springing out will in turn cut all the neighbouring convolutions (2 included), thereby creating an induced E.M.F. and current in such as 2, but in exactly the opposite direction to that flowing from the source, *i.e.* the main supply.

These actions manifestly occur between every turn, and all the other turns, throughout their entire lengths, and the action of every turn in setting up the so-called *reverse*, *counter*, or *back* E.M.F.'s in all the other turns, by thus acting *inductively* on one another, is known as the phenomenon of '*self-induction.*' The self-induced E.M.F.'s, it will be seen, all act in one common direction, opposite to the main E.M.F. of the circuit, and therefore they combine to form an E.M.F. which is commonly termed the *counter* or *back E.M.F. of self-induction.* With unidirectional, direct, or continuous current, as it is variously termed, of constant strength, the phenomenon of self-induction has no meaning, and, in fact, does not exist. With fluctuating direct currents it is an important phenomenon, and is deleterious in its effects, as, for instance, in telegraphy, where, if not partially counteracted, it reduces the speed of signalling. With rapidly intermittent or alternating currents self-induction is of the most extreme importance, acting, as it does, in some cases detrimentally, in others being of vital necessity to the successful operation of appliances. Its properties and effects with such currents will be considered in considerable detail in a later chapter.

Forms of Inductive Circuits.—Now a little consideration will show us that the amount of self-induction possessed by an electrical circuit will wholly depend on its geometrical form. In Fig. 93 four of the typical forms of circuit met with in everyday work are shown. It may be supposed, for the sake of argument, that each of the forms A to D possesses the same resistance to direct currents, the same number of spirals (whether double or single), and is connected successively to the same source of E.M.F. Then form A has practically no self-induction, and is typical of that used in all standard known resistances (*vide* p. 88). It will be seen that a current entering at one of the terminals T flows as many times round the helix in one direction in reaching the innermost bend as it does in the opposite direction. Consequently the magnetic fields set up by the clockwise and counter clockwise currents flowing in this '*doubly wound*' coil neutralise one another if the turns of the double winding are close together. In fact such a coil usually exhibits even a very small electro-static capacity.

Form B will have a very small self-induction; form C, with non-magnetic core, more still; and, finally, form D, in which the turns surround an iron core, will have the greatest self-induction of all. If the same current strength be started successively in forms A to D (Fig. 93), the momentary self-induced E.M.F. and resulting momentary current tend to '*demagnetise*' the ordinary field produced by the current from the source. In consequence no spark occurs at the contacts so closed, but the main current is unable to attain its final strength at once. On stopping the main current, however, a bright spark occurs at the point of breaking in form D, a less bright one with C, a less one still with B, and a scarcely perceptible spark with A. This spark is due to the so-called extra-current, due to self-induction, for the self-induced E.M.F. at the break sets up a magnetising current

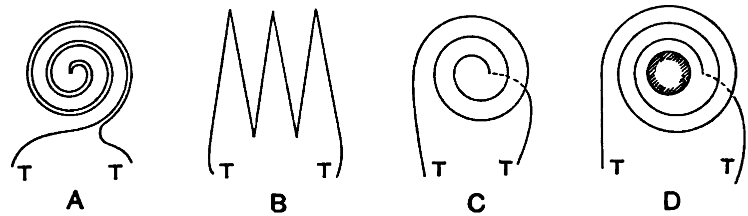


FIG. 93.—Forms of Circuit for Self-Induction.

which momentarily increases the main current. This effect in turn prevents the current dying out instantaneously.

In circuits having the form D, which, owing to the turns being linked with a vastly increased field due to the presence of I, sometimes has a considerable self-induction. A person in contact, with the contacts broken, may receive a dangerously strong shock and be badly burnt by this momentarily induced E.M.F. and current. Self-induction in a circuit opposes every change of current strength in that circuit, and tends to produce constancy, like the action of a heavy fly-wheel on an engine, which by reason of its inertia and momentum tends to give constancy in speed.

Coefficient of Self-Induction.—Now let us suppose that a current of electricity flows through a circuit which is far removed from any magnetic material. The permeability μ of the surrounding medium under these conditions will therefore be constant, and the number of lines of force N produced by the current A in that circuit will be directly proportional to this current, so that any change in the latter will produce a proportional change in the former.

This relationship may be expressed in the form

$$N \propto A,$$

or

$$\frac{dN}{dt} \propto \frac{dA}{dt},$$

where a very small change dA in the current causes a correspondingly very small change dN in the number of lines of force produced; but since we have direct proportionality between N and A, we may write

$$N = LA,$$

or

$$\frac{dN}{dt} = L\frac{dA}{dt},$$

where L is a constant for the circuit in question, which is termed the '*coefficient of self-induction*' of the circuit.

Now since we may write the above relation in the form

$$L = \frac{N}{A},$$

we at once obtain our definition of the *coefficient of self-induction*, which is '*the number of lines threading, passing through, or linked with a circuit when unit current flows through it.*'

The coefficient L of self-induction of an electrical circuit, in a medium of constant permeability μ, is constant for all values of current, and depends only on the geometrical form of the circuit. If the medium is a magnetic substance, such as iron, then μ varies with the current, but not proportionally, and therefore L will vary with the current—*i.e.* with the degree of magnetisation. The term $L\frac{dA}{dt}$ is equal to the E.M.F. of self-induction, and therefore we see that the more rapid the change (as denoted by $\frac{dA}{dt}$) of current strength the higher the self-induced E.M.F.

The analogy has already been drawn between the electrical inertia of a circuit, *i.e.* its self-induction and the inertia of a moving mass. In the case of a fly-wheel of moment of inertia I, revolving freely with an angular velocity ω, the energy stored up in it is represented by $\frac{1}{2}I\omega^2$. So it is in an electrical circuit of self-induction L, and carrying a current A, the energy stored up in the magnetic field in virtue of the self-induction can be shown to be $\frac{1}{2}LA^2$. It is this stored or pent-up energy which is given out again when the field is demagnetised by breaking circuit, and is the real cause of the spark on breaking a circuit.

Practical Unit of Self-Induction.—In dealing with self-induction it is necessary to adopt a unit in terms of which its numerical value can be obtained. The practical unit is one of modern origin, and can be shown to be derived from the ohm (as unit of resistance) and the second (as the unit of time). In scientific parlance, self-induction is said to have the dimensions, – Resistance × Time, and since resistance

is represented by a velocity (*i.e.* length/time) in the absolute electro-magnetic C.G.S. system of units, therefore self-induction is represented by, $-\frac{\text{length}}{\text{time}} \times$ time, *i.e.* by a *length*. An ohm in the above system is represented by a velocity of 10^9 cms. per sec., or by Ohm's Law—

$$1 \text{ ohm} = \frac{1 \text{ volt}}{1 \text{ ampere}} = \frac{10^8 \text{ C.G.S. units}}{10^{-1} \text{ C.G.S. units}} = 10^9 \text{ C.G.S. units.}$$

Thus the practical unit of self-induction = 10^9 C.G.S. units; Profs. Ayrton and Perry have proposed to call it '*a secohm*' (from second and ohm); another name given to it is '*a quadrant,*' because an earth quadrant through Paris is just 10^9 cms. long. The name most commonly adopted is '*the Henry,*' in honour of Prof. Joseph Henry who did so much valuable research in the subject of electro-magnetic induction.

We may now define our practical unit as follows:—

Any electrical circuit is said to have a self-induction of 1 *henry when, on starting or stopping a current of* 1 *ampere in it, the linkage of lines of force of its own magnetic field with the circuit is* 10^9 (or 1,000,000,000).

Numerical Calculation of Self-Induction.—We may now deduce an expression for the value of the self-induction of a typical form of magnetic circuit very commonly met with in several most important electrical engineering appliances. Take the form of circuit represented in Fig. 64, p. 133, consisting of a circular ring of magnetic material of uniform cross-sectional area S sq. cms., closely overwound with T turns of insulated wire. Let the length of the mean circumference of the ring be l cms., and μ the magnetic permeability of the ring when a flux-density B lines per sq. cm. is created by a current of A amps. Then from p. 131 we have the magnetising force

$$H = \frac{4\pi}{10} \cdot \frac{AT}{l} \text{ C.G.S. units,}$$

and from p. 137 we have

$$B = \mu H = \frac{4\pi AT\mu}{10l} \text{ lines per sq. cm.}$$

∴ the total flux through the ring and coil is

$$N = BS = \frac{4\pi AT\mu S}{10l} \text{ lines of force,}$$

and the total linkage between lines of force and turns

$$= NT = \frac{4\pi AT\mu ST}{10l} = \frac{4\pi AS\mu T^2}{10l}.$$

Hence the self-induction of the ring coil

$$L = \frac{4\pi AS\mu T^2}{10^9 10l} = \frac{4\pi AS\mu T^2}{10^{10} l} \text{ henrys.}$$

We thus see that $L \propto T^2$, *i.e.* to the square of the number of turns on the coil, for every turn acts inductively on every other turn. If the surrounding medium is non-magnetic material, μ will $= 1$, and an enormous number of turns will be required to produce a self-induction of 1 henry.

Since μ varies with B, and therefore with A, the above value of L will vary with the current A when magnetic cores are used. The magnetic induction in the cores of electro-magnets and the pull on their armatures is affected by the self-induction of the coils with a fluctuating direct current. Thus if the current rapidly falls, the pull momentarily increases due to the momentarily induced *magnetising* current helping the main current. Exactly the opposite action occurs if the current suddenly increases. A quick-acting electro-magnet, or one required to be sensitive to variation of current such as is used in many telegraphic instruments, should have as small a self-induction as possible. To obtain this the coils should have as few a number of turns as possible and be placed at the end of short cores.

Mutual Induction.—This is a phenomenon which occurs when two electrical circuits, each carrying current, are within the influence of and can therefore act inductively on one another.

The '*coefficient of mutual induction*' of two circuits or coils may be defined as the number of lines of force, mutually embraced by, or linked with, or common to, or which traverse *both* circuits or coils, when each carries unit current and there is no other field than those due to such currents. The coefficient, which is usually denoted by the symbol M, depends upon the form and relative positions of the two circuits, as well as on the permeability μ of the surrounding medium. Consider for a moment the two telescopic coils shown in Fig. 87, p. 186; the value of M for some such position as that depicted would be much less than the value it would have if the coil C enclosed P, the centres of their lengths coinciding. In this latter position M would be a maximum and be given by

$$M = \sqrt{L_1 L_2},$$

where L_1 and L_2 are the coefficients of self-induction of P and C. The introduction of an iron or other magnetic core to the interior of the inner coil will greatly increase the value of M, their mutual induction. This is obvious from the increase of mutual linkage which would ensue, but it can also be seen to be the case from the increase of L_1 and L_2 in the above relation. Mutual induction, like self-induction, is measured in henrys, for it can be seen from the above reasoning that a close similarity exists between the two phenomena.

Numerical Expression for Mutual Induction.—Let us now consider the magnetic circuit mentioned on page 133, viz. the ring, but instead of it being overwound with only one coil, let there be a second and distinct coil of T_2 turns wound over the first one having T_1 turns.

If now unit current (C.G.S. units) flows through the primary of T_1 turns, we have the magneto-motive force due to it,

$$\text{M.M.F} = 4\pi T_1,$$

and the magnetic resistance of the magnetic circuit

$$R = \frac{l}{S\mu}.$$

Therefore the total flux N in the core will be

$$N = \frac{\text{M.M.F}}{R} = \frac{4\pi T_1 S\mu}{l} \text{ lines of force,}$$

and these are linked with the secondary coil of T_2 turns. Hence the coefficient of mutual induction of the coils is

$$M = \frac{4\pi T_1 T_2 S\mu}{l} \text{ C.G.S. units}$$

$$= \frac{4\pi T_1 T_2 S\mu}{10^9 l} \text{ henrys.}$$

If the primary current has a value A amps. other than unity, then the mutual linkage = MA, and

$$M = \frac{4\pi T_1 T_2 A S\mu}{10^{10} l} \text{ henrys.}$$

Comparing this last equation with that for L on page 198 we see that

$$M = \sqrt{L_1 L_2}.$$

The question of mutual induction is very important in its relation to the behaviour and efficient action of certain well-known and important appliances in electrical engineering, *e.g.* the so-called alternating current static transformer and the ordinary Ruhmkorff induction coil, p. 187, or sparking coil, as it is often termed, as well as in other apparatus which will be treated in a later chapter. The ways and means of measuring self- and mutual-induction cannot be treated here, but will be found given in considerable detail in the author's work mentioned on page 101. It may, however, be instructive to give the actual measured values of self- and mutual-induction in the case of some coils and appliances, in order to indicate to the reader what might be the values in other instances.

A. Two *contiguous* and *concentric* hoop-shaped coils (planes coinciding) of which the outer coil has a mean diameter = 44 cms., resistance = 36 ohms, number of turns = 630; the inner coil a mean

diameter = 39 cms., resistance = 23 ohms, number of turns = 460; width of both coils = $1\frac{7}{8}''$. The maximum value of the self-induction of the two hoops connected in helping series $L = 0\cdot768$ henry and mutual-induction between the two separate coils = 0·158 henry.

B. A small straight cylindrical solenoid or coil wound with 1000 turns, and having a winding length = 5″, outside diameter of coil $2\frac{1}{4}''$, inside diameter of coil $1\frac{3}{16}''$, soft iron solid core 6″ long × 1″ diameter.

Self-induction (without iron core) = 0·0102 henry.

„ „ (with „ „) = 0·0442 „

C. In the Siemens' 'Precision' Wattmeter for currents up to a maximum of 12·5 amperes in the fixed thick wire coil, we have:—

Fixed coil:—Number of turns = 32; resistance = 0·0374 ohm; self-induction $L = 0\cdot000056$ henry, size slightly larger than the moving coil.

Moving coil:—Number of turns = 400 carrying 0·03 amp.; resistance = 100 ohm; self-induction $L = 0\cdot0088$ henry, size about $1\frac{1}{4} \times 1\frac{1}{4}$ inches.

The mutual-induction between fixed and moving coils when the pointer is at zero, and they make an angle of about 45° to one another = about 0·00016 henry; this becomes 0 when the planes of the coils are at right angles to each other.

The following examples will make the application of the foregoing formulæ clearer to the reader:—

Example 1. Find the approximate self-induction of a coil of wire comprising 1000 turns, wound on a closed magnetic circuit of iron. The length of the mean path of the lines of force = 50 cms., the cross-sectional area of the magnetic circuit 4 sq. cms., its permeability μ being 2000 when the current of 5 amperes flows through the coil.

From the above relation we see that the self-induction—

$$L = \frac{4\pi AS\mu T^2}{10^{10} l} = \frac{4 \times 3\cdot1416 \times 5 \times 4 \times 2000 \times (1000)^2}{10^{10} \times 50} = 1\cdot0053 \text{ henrys.}$$

2. How many turns of wire would be needed to give the above self-induction in question 1 if air be substituted for the iron?

By transformation—

$$T^2 = \frac{10^{10} l L}{4\pi AS\mu}$$

$\therefore$

$$T^2 = \frac{10^{10} \times 50 \times 1\cdot0053}{4 \times 3\cdot1416 \times 5 \times 4 \times 1} = \frac{10000000000}{4} = 25 \times 10^8,$$

$\therefore$ the requisite number of turns—

$$T = \sqrt{25 \times 10^8} = 50{,}000.$$

3. If the coil in example 1 be overwound with another separate coil of 500 turns, what will be the value of their mutual-induction? Here

$$M=\frac{4\pi\times 1000\times 500\times 5\times 4\times 2000}{10^{10}\times 50}=0\cdot 5026 \text{ henry.}$$

QUESTIONS ON CHAPTER VI

[*Supplement all Answers with Sketches when possible.*]

1. If the north-seeking end of a magnet be thrust into a coil of wire the ends of which are joined together, what will be the result? Illustrate by means of a sketch. (C. and G. Prelim. 1903.)

2. How does the absorption of a condenser introduce difficulty in the measurement of capacity, and how can this be reduced, both in the construction of the condenser and in its use? What is meant by 'dielectric hysterēsis'? Explain its bearing in leading you to select a particular substance for the dielectric in the construction of a condenser for alternate current work. (C. and G. Hons. Sect. I. 1899.)

3. A condenser loses half its charge in an hour: what is the percentage loss per min.? Would such a condenser be considered a good or an inferior specimen? If a good condenser be connected through a resistance with a constant pressure circuit, and then be removed and discharged through another resistance, what is the proportion of energy spent in each of the resistances? (C. and G. Hons. Sect. I. 1897.)

4. How are the pull and self-induction of an electro-magnet connected? (C. and G. Ord. 1895.)

5. Why does an electro-magnet spark on breaking the exciting circuit? (C. and G. Ord. 1895.)

6. How does the slipping of a copper tube over the core lessen the spark of an induction coil? (C. and G. Ord. 1895.)

7. One of the Ferranti mains between Deptford and London has a capacity of 3 mfds. What is the work stored in it in ergs, if the inner and outer conductors are charged to a P.D. of 10,000 volts? (C. and G. Ord. 1892.)

8. A condenser having a capacity of 2 mfds. is connected to two terminals maintained at 2000 volts: how much work is taken from the terminals, and how much can be got out of the condenser again? (C. and G. Ord. 1895.)

9. How could you combine 4 condensers, each having a capacity of 1 mfd., so as to produce a capacity of 0·75 mfd.? (C. and G. Ord. T. and T. 1901.)

10. What is a 'condenser,' and how is it constructed, and for what different purposes is it used in practical telegraphy? (C. and G. Ord. T. and T. 1901.)

11. What is meant by 'self-induction,' what is its unit, and how can its value be measured? (C. and G. Ord. T. and T. 1901.)

12. Sketch the lines of magnetic force created by a solenoid traversed by a current, and give the formula connecting the current, the number of turns, and the number of lines of force. (C. and G. Hons. T. and T. 1901.)

13. Draw a diagram showing two parallel telegraph wires earthed at each end, and show by distinctive arrows the effects of (*a*) static, (*b*) electro-magnetic induction on No. 2 wire when a positive current is started on No. 1 wire, and when it ceases. (C. and G. Hons. T. and T. 1901.)

14. When a metallic telephone circuit is erected on a line carrying high-speed telegraph circuits, what are the principal conditions necessary to ensure a balance against (*a*) electro-static, (*b*) electro-magnetic induction? Which is the more difficult to deal with and why? (C. and G. Hons. T. and T. 1901.)

15. Describe in detail each step in the construction, testing, and adjusting of a

condenser. Mention all the uses to which electric condensers are put in practice. (C. and G. Hons. Sect. I. 1901.)

16. Distinguish between 'static' and 'dynamic' induction. (C. and G. Ord. T. and T. 1897.)

17. Describe what is meant by the self-induction and the capacity of a circuit, and state what relation these bear to each other in practical telegraphy. (C. and G. Hons. T. and T. 1897.)

18. For what purpose are shunted condensers used in telegraph circuits? Describe how they act. (C. and G. Hons. T. and T. 1897.)

19. What is the formula giving the magnetising force of a solenoid, the current and the number of turns of the conductor being known? What is the effect of introducing a soft iron core? (C. and G. Hons. T. and T. 1897.)

20. Describe in general terms the meaning of 'electro-static capacity' and its effect on the working of telegraph or telephone lines. (C. and G. Ord. T. and T. 1900.)

21. Give a simple rule for the direction and magnitude of the E.M.F. induced in a wire passing the face of a north-seeking pole, and for the force exerted on it per ampere. (Ord. 1899.)

22. Why should a single alternating current main not be led through an iron pipe? (Prelim. 1899.)

23. What is meant by '*electrification*' in a submarine cable, when the cable is tested for insulation? (Ord. T. and T. 1900.)

24. Two insulated wires of equal length have each a conductor whose diameter is 100 mils, but the external diameter of the insulating covering of one wire is 200 mils, and of the other 500 mils: what are the relative electro-static capacities of the two wires? Log $2 = 0{\cdot}30103$. (Hons. T. and T. 1900.)

25. Give a diagram of the core, windings, and connections of an induction coil, and explain the uses of the various parts. (Prelim. 1902.)

26. What is the capacity F. of 2 condensers F_1 and F_2 when joined 'in cascade'? (Hons. Teleg. 1902.)

27. The capacity of one mile of copper wire 50 mils in diameter covered with gutta-percha to a thickness of 62·5 mils is 0·29 mfd.: what is the capacity of a wire 100 mils diameter covered to a diameter of 390 mils? Log $3{\cdot}5 = 0{\cdot}5440680$ and Log $3{\cdot}9 = 0{\cdot}5910646$. (Hons. Teleg. 1902.)

28. What is the cause of 'sparking' at the contact points of a telegraphic relay? what is its effect and how can it be prevented? (Hons. Teleg. 1902.)

29. When iron pipes are used as conduit for alternate current conductors, why is it important that the 'lead' and 'return' should be in the same tube? Give reasons for your answer. (Prelim. 1903.)

CHAPTER VII

ELECTRICAL AND MAGNETIC INSTRUMENTS

IN the preceding chapters we have dealt at some length with important fundamental phenomena and principles pertaining to the subjects of electricity and magnetism. We may now turn our attention to the application of such principles in the construction of instruments for use in the many measurements which these subjects entail. Confining ourselves for the present to instruments used in *electrical* measurements, we may, for convenience, divide them all into two classes, namely: (1) those for measuring very small currents; (2) those for measuring much larger currents of electricity. The former come more particularly under the heading of 'delicate' instruments, and are usually termed '*galvanometers*.'

Irrespective of any arbitrary classification such as the above, the principles on which they all work are based on one or other of the properties or effects of an electric current detailed on page 35. Consequently there are four distinct types of electrical measuring instrument used in electrical engineering work, corresponding to the following effects, namely: (1) electro-magnetic; (2) thermal; (3) electro-static; (4) chemical.

The number of different forms belonging to each type, devised by the various makers, each claiming some advantage over the other, is considerable. Space, however, will not permit of the description of more than one prominent example of each distinct type of instrument in common use. For others, the reader must refer to books dealing with this subject exclusively, *e.g. Electrical Engineering Measuring Instruments*, by the author. By far the greater number of galvanometers in everyday use work by the '*electro-magnetic*' *effect* of a current, and these may be subdivided into: (*a*) *Moving-needle* galvanometers; (*b*) *Moving-coil* galvanometers.

Fig. 94 indicates the principle of a form of moving-needle galvanometer largely used with portable Wheatstone bridges. It consists of

a flat-shaped bobbin having an internal aperture, and on which is wound a coil C consisting of a large number of turns of fine, insulated wire, usually having a resistance of from 1000 to 2000 ohms. Inside this coil is a strongly magnetised steel needle *ns*, which, with its attached pointer P, is capable of rotating through an angle of about 90° on a vertical spindle supported in jewelled centres. If the current flows round the coil C (only one turn of which is shown for simplicity) in the direction shown by the arrows, north polarity will be developed at one end NN of the solenoid, and south polarity at the other end SS, whence, by the rule given on page 4, the needle *ns* and pointer P will turn counter-clockwise over the graduated scale I. If the current is reversed in direction, P will turn clockwise for the polarity of the pivoted needle shown.

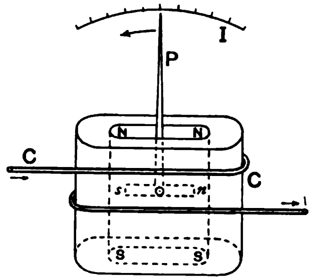


FIG. 94.—P.O. Galvanometer (Principle).

The general appearance of one form of this instrument is shown in Fig. 95, and it will be seen that a strip of mirror is let in under the scale for the purpose of avoiding *parallax* in reading the deflections of the pointer P. In connection with this it should be remembered that the actual deflection of a pointer on any scale is the reading on the scale *perpendicularly* under the pointer. This differs more and more from the reading of the pointer viewed *sideways*, as its distance from the scale increases. Now the image of P in the plane mirror is always perpendicularly under P, so that wherever P is seen to cover its image, the true deflection can be read off, and thus the observer knows when he is viewing the position of P perpendicularly. The small button seen on the side of the containing case at the back (Fig. 95) is for clamping and releasing the pivoted needle to prevent the centres being damaged by rough handling during transit. The two terminals of the coil mounted on ebonite blocks are shown on the right- and left-hand sides of the case respectively. Owing to the large number of turns of wire on the coil, and to the delicate pivoting

FIG. 95.—General View of Galvanometer.

of the moving system, this form of galvanometer is very sensitive to small currents, and has the advantage of being very portable.

The sensitiveness is such that a current of $\frac{1}{10000000}$ of an ampere gives 1° deflection on the scale. Another form of moving needle galvanometer of much greater sensitiveness than the preceding one is shown in Fig. 96. This is commonly known as the *Kelvin* or *Thomson astatic* reflecting galvanometer, and consists, as seen in the figure, of two thick slabs of ebonite hinged to an ebonite base which rests on three levelling screws. Each slab carries two somewhat flat coils which are let into it, the one at the top and the other at the bottom, each wound with a great number of turns of very fine silk-covered copper wire. These four coils are all connected in series with one another across the two terminals seen on the base to the left, and in such a way that the adjacent faces of the top pair and of the bottom pair have opposite polarity respectively, while at the same time the polarity of the top and bottom coils of a slab is reversed.

FIG. 96.—Thomson Astatic Reflecting Galvanometer.

The coils are so arranged that when the ebonite slabs are shut up against the central vertical sheet, the magnetic axes of the two top coils line up with one another, and a small spherical cavity is formed between them. The bottom pair of coils are similarly arranged, the two coils on the slab E at the back, together with the suspended system, being shown symbolically in Fig. 97, which will make the arrangement clearer. Suspended by means of a fine fibre F of cocoon silk from a brass cap H, which is fixed to the top of the central vertical sheet, is a rigid aluminium wire W. This wire is a trifle longer than the distance between the centres of the top and bottom coils, and has attached rigidly to it, near the ends, two systems of small highly magnetised steel needles *ns* and *sn*.

As seen in Fig. 96, and indicated also in Fig. 97, each system comprises three needles parallel to one another, and having poles of similar polarity all pointing one way. The two systems are, however, parallel,

but the reverse of one another as far as polarity is concerned. Midway between the coils and fixed to WW is a concave mirror M with a vane V of mica or aluminium foil. The two systems of needles *ns* and *sn* have just room enough to move in the cup-shaped cavity C of the coils, as also the vane V with the attached mirror M, in the slot provided, as WW turns through a small angle. The two systems of needles (composed of three each in order to gain strength) are said to be arranged *astatically*, but owing to one set usually being stronger than the other, absolute astaticism seldom exists, which is an advantage, as it enables the horizontal component of the earth's magnetic field to exert some slight control on the moving system, thereby keeping it at zero.

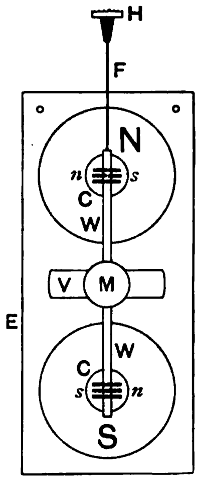


FIG. 97.—Principle of Thomson Astatic Reflecting Galvanometer.

When a current is sent through the coils of the galvanometer the moment of the deflecting couple acting on the whole system will be the sum of the moments of the couples, *i.e.* the sum of the several products of either of two equal parallel forces (not in a line), into the perpendicular distance between these forces, acting on the two sets of needles separately. The wire W will therefore be turned by the needles through a certain angle which will depend on and increase with: (1) the number of turns on the coils; (2) the strength of the needles; (3) the weakness of the controlling force exerted either by the earth or separate controlling magnets. The motion, which is damped through the churning of the air by the moving vane V, is indicated by the reflection, on to a fixed scale, of a beam of light projected through a slit on to M, through the central aperture in the slabs. The effect at the scale, which is usually 40″ away from the mirror, is that of a moving slit or bright line, which, it can be shown, moves through an angle twice as great as M itself. Thus the reflected beam of light acts as a long, weightless pointer of the above length, and the motion of the moving system is greatly magnified. Owing to the enormous number of turns of wire on the coils, this type of galvanometer seldom has a resistancce less than 10,000 ohms, and sometimes as much as 100,000 ohms. Owing to its extreme sensitiveness it is usually employed in the measurement of insulation resistances, the currents with which are sometimes not greater than $\frac{1}{2000000000}$ of an ampere.

Fig. 98 illustrates a still more elaborate form of Thomson

(Kelvin) astatic galvanometer, as made by Mr. R. W. Paul, London. The general principle is, however, precisely similar to that just considered, there being four coils arranged astatically and wound with extremely fine wire to a resistance of 100,000 ohms. The front

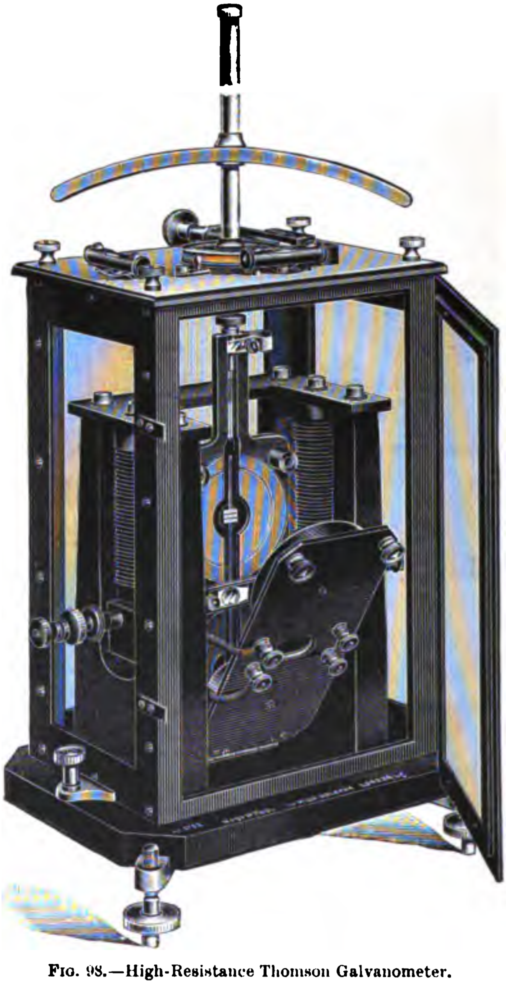


FIG. 98.—High-Resistance Thomson Galvanometer.

slab carrying the two front coils is shown leaning outwards in order to show the interior more clearly. The suspension, consisting of a very fine fibre of quartz or cocoon silk, is made longer than usual to minimise torsional resistance, and an extremely high insulation resistance of the electrical parts is obtained by supporting the terminals, etc., on the two corrugated ebonite pillars shown inside the glass

case. Two spirit-levels at right angles to one another are fixed to the top of the case for accurately levelling the instrument, and thus ensuring freedom to the moving system. The curved bar on the top is a controlling magnet capable of being turned by extremely small amounts by a worm and worm-wheel seen in the centre of the top of the case.

Another extremely sensitive form of moving-needle galvanometer, employed mainly in the measurement of transient or momentary currents set up in a circuit by the passage of a small quantity of electricity, and called a '*ballistic*' galvanometer, is shown in Fig. 99. It will be noticed that only one pair of coils are employed, one of

FIG. 99.—Ballistic Galvanometer.

the coils being hinged, and shown swung back, to enable the moving magnet system to be seen.

This consists of an arrangement of four magnets, of which two of the bell- or U-shaped steel magnetic needles are at the centre of the coils, and one at both the top and bottom. The four needles are fixed astatically to a rigid aluminium wire, which is in turn suspended by a fine fibre of cocoon silk from the head seen above it. The two inside needles are acted on by the current flowing through the two coils (in series) in the ordinary way, while the needles outside are acted on by the outer turns of the coils, and are in astaticism with the inner two. The small concave or plain mirror is carried by the wire above the upper needle. The controlling magnets at the back and on the top of the brass enclosing case shown to the left are for the purpose of obtaining easily any strength of controlling field for the purpose of altering the sensitiveness of the instrument.

A galvanometer constructed in this way with a heavy moving system is highly *ballistic*, *i.e.* the moving system will continue swinging to and fro for several minutes. The galvanometer shown is usually wound with such a number of turns of very fine silk-insulated copper wire that its resistance is about 10,000 ohms, but of course any other winding and resistance can be employed. In the case of such delicate high-resistance galvanometers as the last two described, it is most important for them to be highly insulated. This is more especially needful when they are used for measuring very high or insulation resistance, since in the latter case the actual current through the galvanometer will be the sum of the current passing through the resistance under measurement, and that due to leakage from the instrument to earth. Thus the resistance measured would appear smaller than it really was, and unless a correction be applied, its calculated value would be less than its true value.

High insulation in such instruments is obtained by using a highly polished ebonite base, the working parts being supported on this again by corrugated ebonite pillars (*vide* p. 111). It should be remembered that any ordinary form of reflecting galvanometer can be employed as a *ballistic galvanometer* by weighting the moving system (whether coil or needles). This causes the oscillations of the latter to be much slower, and tends to prevent the motion occurring before the whole quantity of electricity has been discharged through the coils of the galvanometer. This condition is essential in order that the relation below may hold true. Furthermore, the various parts of the moving system of a ballistic galvanometer should be of such a form and size as to cause the least amount of damping possible, whether produced through air-churning or otherwise. For example, the attached mirror should be small in diameter, and if this and the needles are fixed to a strip of mica or aluminium vane, the latter should be replaced by a wire. *The number of seconds taken by the pointer or spot of light in moving from any one position on the scale to the same position when next moving in the same direction* is called the *periodic time of oscillation* (T). Now the quantity of electricity Q in coulombs discharged through a ballistic galvanometer may be evaluated as follows :—

Let the first throw or angular deflection of the needle be $\theta°$, and let the steady angular deflection produced by a steady current of A amperes flowing through the galvanometer be $d°$.

Then for very little, or no, damping, we have

$$Q = \frac{T}{\pi} \cdot A \cdot \frac{\sin \frac{\theta°}{2}}{\tan d°} \text{ coulombs,}$$

but for the small angular motions (usually not greater than 6° or 7° of arc) met with in reflecting instruments

we have
$$\frac{\sin\frac{\theta^\circ}{2}}{\tan \theta} = \frac{1}{2}\,\frac{\theta}{d} \text{ very nearly.}$$

Hence
$$Q = \frac{T}{\pi} \cdot \frac{A}{2} \cdot \frac{\theta}{d} \text{ coulombs.}$$

If the damping effect is appreciable, which can be seen by the oscillations of the needle diminishing rapidly, it must be allowed for by multiplying the above equations by a correcting constant. This, however, is dealt with at some length in the author's work, *Practical Electrical Testing*, to which the reader is referred.

D'Arsonval, or Moving-Coil, Galvanometer.—This form of galvanometer, originally devised by M. D'Arsonval, is practically the inverse of the moving-needle type. The principle is used to an enormous extent at the present day for both laboratory and commercial instruments, owing to the cheapness and simplicity of construction, coupled with several advantages possessed by this kind of instrument over the previous ones. The construction will be understood from a reference to Fig. 100. It consists of a highly magnetised U-shaped compound steel magnet M composed of several U's of allevard or tungsten steel assembled side by side and clamped together. Midway between the poles is fixed a solid, soft-iron cylinder or keeper K. Free to turn in the narrow air-gap between the poles and K is a light suspended coil, wound with from 200 to 600 turns of very fine insulated wire C, which usually only weighs from about 3 to 4 grms., complete with mirror and suspension strips, and has a resistance (depending on the sensitiveness required) varying from 30 to 600 ohms. This coil is strung between a supporting head H and foot F by two fine phosphor bronze stripes WW which serve not only to lead the current into and out of the moving coil, but also as a control, causing the coil always to return to its initial zero position for no current flowing through it. The motion of C is observed by the reflection of a beam of light from the attached mirror *m* on to a fixed scale.

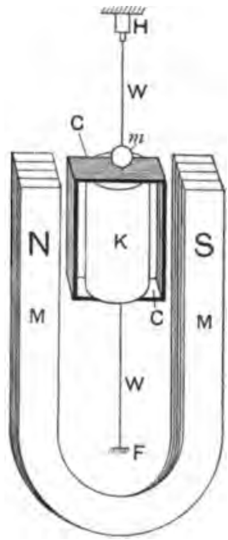


FIG. 100.—Principle of D'Arsonval Galvanometer.

The fixed points H and F are connected by wires to the two

terminals of the galvanometer (not shown in Fig. 100). The object in building up or laminating M is to obtain the maximum possible strength of magnetic field for a given size (*vide* p. 10), and that of K for concentrating this field through the coil (*vide* Figs. 5 and 6), thereby increasing the sensitiveness for a given instrument. The induction-density due to M in such instruments is about 700 lines per sq. cm. The turns of the coil C can, of course, be wound on a very light non-metallic frame, or otherwise, in the former case, the instrument acts more or less ballistically. If, however, it is wound on a metallic frame such as aluminium strip foil, the currents *induced* in the frame itself, *vide* p. 194, as the current in the coil causes this latter to move in the permanent field, damps the rapid motion and causes it to be *aperiodic* or *dead-beat.* In other words, the coil is instantly deflected to its new position and stops there without oscillations to and fro for some time. Thus readings may be taken in rapid succession if necessary, avoiding loss of time. The action of the instrument is simply that mentioned on p. 125, namely, that the magnetic field created by the current flowing in the coil C tends to turn so as to coincide in direction with that of M, the deflecting moment and angular motion increasing directly proportionally to the current throughout the small angular motion (usually only 6° or 8°) of the coil.

The sensitiveness of the D'Arsonval form, though not so great as that of the Thomson moving-needle type, is ample for most purposes. It can easily be obtained to the extent that 1 volt, applied to the instrument with 2000 megohms in series, produces $\frac{1}{40}$ inch deflection on a scale placed 40 inches away from the mirror.

FIG. 101.—D'Arsonval Galvanometer.

Until quite recently, the very simple but effective construction of D'Arsonval galvanometer indicated in Fig. 101 was that supplied by almost every maker. Some manufacturers, notably Messrs. Elliott Brothers of London, and Crompton and Co. of Chelmsford, are, however, now making a more elaborate form of the instrument, having some advantages over the more simple form. One advantage consists in making the soft iron keeper, the moving coil, its suspensions and their supports, *detachable in one frame* from the U-magnet and base.

Repairs and interchanges of sensibility, etc., can in this way be made in a few seconds with the same instrument.

An innovation by the former of the above-named firms in their so-called *Century D'Arsonval* galvanometer consists in having the aluminium frame on which the moving coil is wound, *split*, and inserting a variable resistance between the two parts. By adjusting this resistance any desired amount of *damping* may be obtained. Another device for damping the oscillations of the coil is that known as the 'Idle Wire' due to Taylor (Patent No. 8181 of 1887).

The Ayrton and Mather Moving-Coil Galvanometer.—This instrument, devised by Prof. Ayrton and Mr. Mather in 1892, is of

FIG. 102.—Ayrton and Mather Moving-Coil Galvanometer.

the reflecting D'Arsonval type, and while working under exactly the same principle as that just described, presents a somewhat novel construction combined with important properties.

A general view of the latest improved pattern made by Mr. R. W. Paul, London, is shown in Fig. 102 with the cover removed. It consists of a brass base, resting on three levelling screws, and carrying the two insulated terminals, a circular level, and a tripod on which a powerful, cylindrically shaped, permanent magnet is securely clamped. A socket-holder, insulated from the metal base, but connected to one terminal, is fixed directly under the gap between the poles of the magnet, and firmly holds in position the outer tube shown in Fig. 105.

The moving coil is of peculiar form, evolved by Mr. Mather from a mathematical investigation, confirmed by experiment, and consists of a large number of turns of fine silk-covered wire, wound into a long narrow coil of the form shown at C in Fig. 103. The form of

cross section of the winding of the limbs is circular, as shown at E in the same figure.

This form of coil is the best for giving the greatest turning force for a given moment of inertia and resistance. It is fixed in a protecting tube which is connected to one end, the other end of the coil being joined to an insulated stud passing through the lower end of the tube. The tube containing the coil and carrying the mirror and suspension clips (seen at the extreme ends) is shown in Fig. 104.

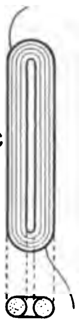


FIG. 103.—Moving Coil of Ayrton and Mather Galvanometer.

For all ordinary purposes, except ballistic work, the moving system of a galvanometer should be aperiodic or dead-beat, *i.e.* come to rest quickly. To effect this, the tube is made of silver, when the eddy currents induced in it as it moves rapidly bring it to rest. For ballistic work in which a long periodic turn is required, the tube is made of ivory. This tube, containing the coil, is suspended by flat bronze strips in an outer brass tube, Fig. 105, cut away in front for most of its length, and fitted with contacts which make connection to the terminals when this outer containing tube is slipped into the fixed socket-holder on the base. The inner coil tube can be clamped during transit by drawing outwards two phosphor bronze strips which pass through a slit in the middle of the outer tube, as shown in Fig. 105. These strips embrace the middle of the coil tube and hold it against the side of the outer tube. The tube swings free of these slips when they are pushed inwards.

A bronze spiral makes the bottom connection to the coil and allows the latter to hang freely. The coil itself, which weighs about 2·5 grammes, is specially treated to avoid the presence of magnetic material in its construction. The suspension tubes are interchangeable and hang from the end of a short flat spring attached to the torsion head of the outer tube. Risk of breakage of suspension through setting down roughly is thus minimised, while an adjustment to zero is at the same time obtained. The periodic time of the aperiodic coils is from 2 to 3 secs. and of the ballistic about 5 secs. The coils are wound to 4 resistances—3, 93, 325, and 1000 ohms respectively, giving 4 sensibilities as follows:—*Aperiodic:* average deflection on scale 1 meter off, 6·5, 25, 50, and 65 mm. per micro-ampere. *Ballistic:* average swing on scale 1 meter off, 30, 100, 200, 250 mm. per micro-coulomb. For the same resistance and periodic time, the sensitiveness of this galvanometer is as great as that of the Kelvin (Thomson) astatic moving-needle instruments.

Holden's Hot-Wire Galvanometer.—A little consideration will

make it evident to the reader that, since all the forms of galvanometer so far described contain either a moving or a fixed permanent magnet, they will not measure an alternating or rapidly reversing current. Those of the moving-needle form would measure such a current if the permanently magnetised needle was replaced by one of soft iron, but with an enormous loss of sensitiveness. On the other hand, the D'Arsonval form would do the same if the alternating current to be measured was sent round the moving coil and the fixed permanent magnet be replaced by a well-laminated one of soft iron magnetised by a coil supplied with current from the *same* source. The keeper K must also be well laminated, and the metal frame on which the moving coil is wound must be replaced by a non-metallic one. Using these and other minor precautions, the author has constructed some very sensitive moving-coil alternating current D'Arsonval galvanometers, and obtained excellent results with them.

FIG. 104.—Moving System of Ayrton and Mather Galvanometer.

FIG. 105.—Outer Tube containing Moving System.

Some time ago, Major Holden devised a form of galvanometer for measuring alternating current based on the *thermal effect* of a current. This instrument, which will measure direct current equally well, is made by Mr. J. Pitkin, of London, and is commonly called a *hot-wire* galvanometer. The principle of this instrument, but not the exact form of construction, is shown in Fig. 106. It consists of a rigid metallic frame FF_1, separated electrically into two parts by the interposition of some insulating material at, say, A. The upper portion of F carries a spring S provided with a torsion-head H, and between this head and a pin carried by, but insulated from, the end of F_1 by an insulating bush I, is strung a metallic wire *ww*. This wire carries a mirror M and a boss or spindle K, round which is wrapped a silk fibre T, the other end being attached to the mid-point of another wire W strung between S and F.

W and *w* are of materials having the same coefficient of expansion by heat, so that atmospheric changes of temperature do not affect the position of M and therefore the indications of the instrument.

Though both W and w are kept taut by the spring S, they are insulated from one another, and the current to be measured can only pass through W. A slight strain is put on the silk coupling T by turning the torsion-head H. When a current, entering at the terminals t, t of the instrument, flows through W, this wire is heated and expands, the sag being taken up by K turning with a corresponding rotatory motion of the mirror M.

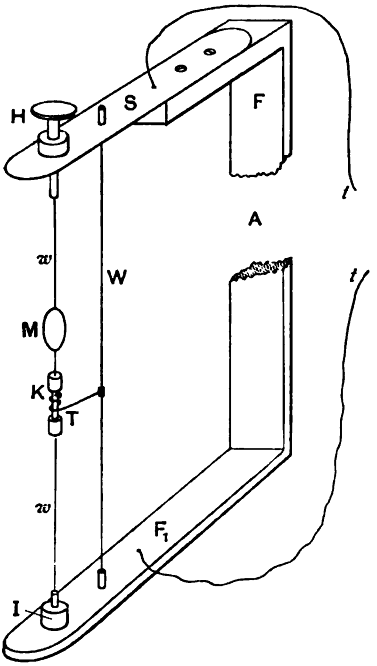


FIG. 106.—Principle of Holden Hot-Wire Galvanometer.

Up to the present we have not touched on the arrangement for enabling the deflections of reflecting galvanometers to be observed. There are many devices for effecting this, an extremely neat and simple one being shown in Fig. 107, which is made by Messrs. Nalder and Co., of London. It consists of a semi-transparent scale, about 18″ long, divided into equal arbitrary divisions of $\frac{1}{10}$″ each. This scale is carried in a frame which slides horizontally (for the length of the slot seen) on a T-piece terminating in a vertical tube or rod. This latter can slide up or down in an outer tube provided with a heavy foot at the bottom and a milled nut at the top, for clamping the sliding tube at any height.

Fixed to the T-piece, which carries the scale, is the lamp-box, containing an electric glow lamp and provided with a condensing or double convex lens at the end of the tube which projects from the side. The rays of light from the lamp are condensed by the lens through which they pass, and are projected in the form of a beam of parallel rays on to the galvanometer mirror, which reflects them back on to the scale, forming an image on the scale of a fine scratch on the lens. In this way the faintest motion of the mirror is observable without the employment of a long pointer to magnify the motion, which would not only be unwieldy, but would also cause the motion to be sluggish by reason of the inertia thus added to the moving system.

Pivot and Fibre Suspensions.—It may be well to note here that

there are two methods of supporting the moving system of a measuring instrument, namely—(1) by a flexible fibre from a fixed support, (2) by pivots.

The first method may be subdivided into (*a*) torsionless, (*b*) non-tortionless suspensions. In the former of these two, the moving system, such as that described in connection with Figs. 96 to 99, is suspended by a fine fibre of unspun silk (usually cocoon), which, if at all fine and long, is practically tortionless. In the second case, the moving system, such as that of Figs. 100 to 106, is suspended by a metallic wire or strip, often of phosphor bronze or platinum-iridium, which not only acts as the suspension, but also serves as the controlling force (by reason of its torsional rigidity) for bringing the moving system back to zero. It also serves very often as a conductor for leading current into and out of the moving system, as, for instance, with the instrument in Fig. 101 and others.

FIG. 107.—Lamp and Scale Stand.

Some moving systems, especially those belonging to portable instruments, are carried on a light steel spindle, the carefully pointed ends of which turn in jewelled centres. The fibre suspension, invariably employed with the most delicate galvanometers, introduces far less friction to the motion of the moving system than the finest pivot and is cheaper, but it necessitates some levelling arrangement, as a rule, to ensure freedom of the moving system before use.

The Duddell Oscillograph.—In the various kinds of galvanometers considered so far, as well as in all other forms working on similar principles, the *Periodic Time* of oscillation of the moving system ranges from a higher limit of something like 20 seconds in highly ballistic instruments to a lower limit of 1 second or a little less in damped ones. Many ordinary forms of galvanometer have moving systems which are highly damped,—*i.e.* extremely dead-beat,—but the inertia of their moving systems prevents them following very rapid fluctuations of current. For example, the pivoted D'Arsonval galvanometer illustrated in Fig. 118 would follow almost exactly the fluctuation of current delivered from a dynamo which is driven from an old-fashioned

gas-engine, but would not move if this current was reversed 50 or 60 times a second.

An instrument capable of accurately following extremely rapid fluctuations and periodic reversals of current is the highly specialised form of moving-coil D'Arsonval galvanometer devised by Mr. W. Duddell, and called the *Oscillograph*. Apart from the arrangement employed for reading its deflections, the principle on which the

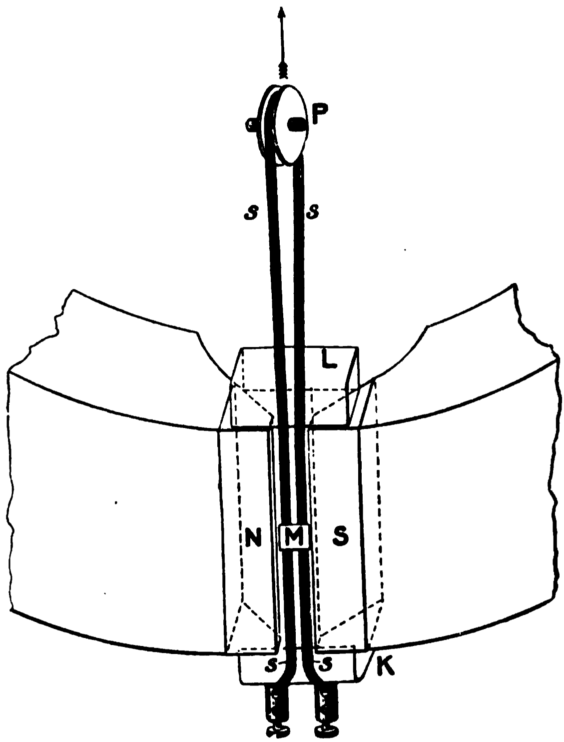


FIG. 108.—Principle of Duddell Oscillograph.

galvanometer itself works will be understood from a reference to Fig. 108. In the narrow gap between the poles N, S of a powerful magnet are stretched two parallel conductors *s*, *s*, formed by bending a strip of phosphor bronze back on itself over the pulley P, which is attached to a light spring-balance. At the bottom ends the strips, which have a resistance of about 5 ohms, are clamped on a block K, while at the top they are held in position by the bridge-piece L.

By altering the tension on the spring stretching the phosphor bronze loop, the *periodic time* of the instrument can be varied at will. Each strip or leg of the loop passes through a separate gap (not shown

in Fig. 108) in the magnetic circuit filled with a viscous oil, over which is placed a small lens.

This lens is held in position entirely by the surface tension of the oil, which it thus keeps in place, the object of the oil being to damp the movement of the strips. A small mirror M (usually about 1 × 0·3 mm.) is attached to the loop, with the longer edge vertical, for indicating its motion. When a current is sent through such a loop—

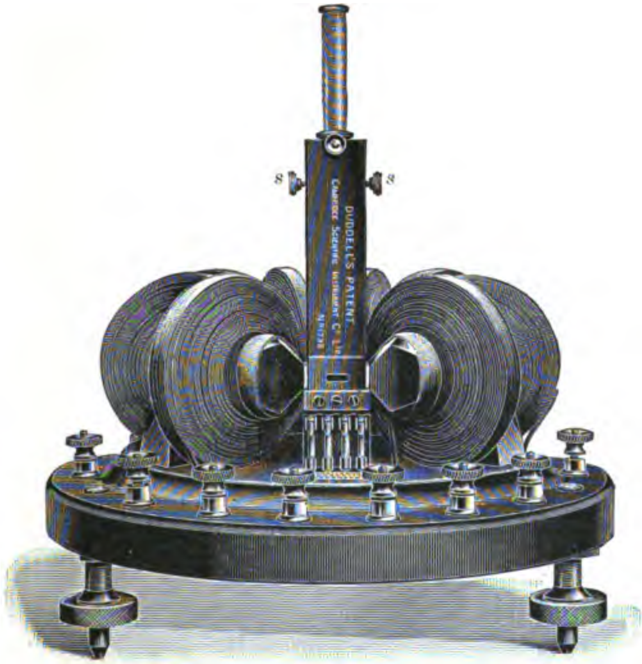


FIG. 109.—Double High-Frequency Oscillograph. General View.

i.e. up one leg and down the other—one leg tends to advance, the other to recede, thus causing M to turn, through a small angle proportional to the current, about a vertical axis. The clearance between the sides of the gaps and the moving strip is only about 0·038 mm., so that the damping effect of the oil is enormous.

Fig. 109 shows the general form of a '*Double High-Frequency Oscillograph*' consisting of two distinct loops (the *single* pattern containing only one loop) and really constituting two single instruments built compactly in one magnetic field. With this *double* form the fluctuation of two currents, or two P.D.'s, or a P.D. and a current, can be observed or measured absolutely simultaneously, the zero line being obtained by means of an additional mirror fixed to the instrument.

Small fuses having a resistance of about 5 ohms, and consisting of very fine wires, which are enclosed in glass tubes and held in position by spring clamps, are fixed below the strips (Fig. 109), but in series with them, and protect the strips from being fused in case of accidental excessive currents.

It will be seen that in this type of the oscillograph the magnetic field in which the loops move is produced by means of a powerful electromagnet wound in 8 sections, the resistance of which all in series is about 360 ohms at 30° C. These are connected in pairs (of two in series) between the 4 pairs of terminals shown, so that by suitably combining them the magnet can be excited direct from 25, 50, or 100 volt continuous current mains. Exact adjustment of exciting current, which is normally 0·28 ampere with all the coils in series, is unnecessary, for, the iron being saturated, a change of 4 % more or less in the current only alters the sensibility by about 1 %. The tangent screw-heads s, s are for bringing the spots of light to zero.

Indicating Arrangements.—The motion of the spot of light reflected from M, which may be oscillating several hundred times per second, in the ordinary class of work for which the oscillograph is intended, would be far too rapid to be followed by the naked eye on an ordinary scale. Consequently one of the following three methods for observing and recording the movements of the spot or spots must be employed:—

(1) By viewing the reflection of the moving spot on the screen in a mirror rotating on a horizontal axis, and situated so that, owing to persistence of vision, the moving spot appears drawn out into a bright time-curve of the variation to be observed. The curve can then be sketched for future reference.

(2) By recording on a photographic plate or film, which is caused to move rapidly at right angles to the plane of oscillation of the beam of light, the motion of the moving spot. This method is very expeditious, gives permanent records free from personal error, and is the only satisfactory one for recording rapid irregular variations.

(3) By the combination of two motions at right angles, one proportional to the instantaneous value of the current through the oscillograph, the other to the time.

The spot now travels continuously along the curve of variation required, which, owing to persistence of vision, appears as a bright stationary curve of light. The method is only applicable to periodic variations, and is operated by the beam of light from the oscillograph mirror M being reflected, before reaching the screen, by an additional mirror, rotated synchronously with the variations to be recorded, on a horizontal axis—*i.e.* right angles to that of the oscillograph mirror M.

In the single and double portable forms of the instrument the electro-magnet is replaced by a permanent one with a corresponding diminution in the periodic time of the instrument. The deflection in this form is observed in the mirror above referred to, which is rotated by hand.

Properties and Uses of the Oscillograph.—The extreme value and importance of this unique form of instrument can hardly be over-estimated, for not only has it the shortest periodic time (ranging from $\frac{1}{1800}$ sec. in the double projection type to only $\frac{1}{10000}$ sec. in the double high-frequency pattern when undamped) of any galvanometer yet made, but also extreme sensitiveness combined with a low total resistance (including fuse) of from 5 to 10 ohms. It is perfectly dead-beat, has practically no self-induction or capacity, and is absolutely free from errors due to hysterēsis.

When it is remembered that with an ordinary well-damped galvanometer having a period of 10 secs., accurate observations can only be made of varying currents and P.D.'s which go through a cycle of variations in not less than five minutes, whereas the oscillograph will accurately record a cycle of variation which takes only $\frac{1}{300}$ of a sec., the extreme value of Mr. Duddell's invention will be appreciated. Its deflection at any instant is accurately proportional to the instantaneous value of the current flowing up one limb and down the other limb of the loop *ss*, Fig. 108, even with cycles of variation occurring at as high a rate as 300 per sec.

The sensitiveness is such that with the normal-scale distance of 50 cms., a deflection of from 3 to 4 cms., but which should not be allowed to exceed 5 cms. each side of zero, is obtained, with from 0·05-0·10 ampere (depending on the form of variation to be measured) through the loop. This, with a tension of 8 ozs. (for pattern shown in Fig. 109), normal exciting current in magnet coils, and using damping oil, corresponds with a sensibility of about 29 cms. deflection on the scale per ampere. The oscillograph may, with the above qualifications, obviously be employed in many determinations of an extremely important and practical nature. For instance, to record the simultaneous changes of P.D. and current in (*a*) an alternating current circuit, (*b*) charging and discharging a condenser or electric cable, (*c*) making and breaking an inductive circuit, (*d*) an arc lamp when hissing, (*e*) the primary of an induction coil, (*f*) the armature coils of a dynamo, etc. We shall see at a later stage how extremely important the measurement (*a*) is to an electrical engineer.

The method of connecting the oscillograph to a circuit for the purpose of measuring the variation of P.D. and current is shown

symbolically in Fig. 110. The P.D. necessary to work the oscillograph when fuses are connected in series with the strips or loops is from 1 to 1·5 volt. The loop intended for recording variations of the main current is connected in series with its fuse f_1, switch S_1, and low resistance R_2 across the terminals of a standard non-inductive low resistance R_3 in the main circuit. If the P.D. at the terminals of R_3 is v volts when a current A amp. flows through it

Then by Ohm's Law $v = AR_3$ volts.

If the resistance of R_3 remains constant for all currents, then the P.D. (v), which the oscillograph loop measures, is directly proportional to the main current A. R_2 is for adjusting the sensitiveness to a round number of amperes per mm. deflection on the scale. The

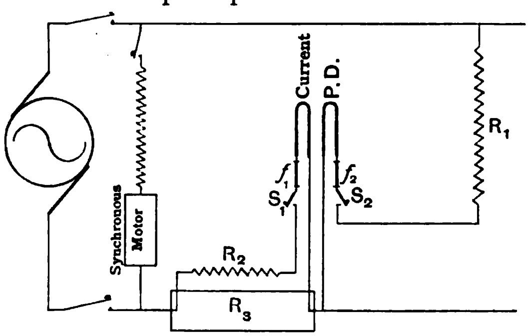


FIG. 110.—Connection of Strips for Measurement of Current and E.M.F.

loop intended for recording variations of the voltage across the mains is in series with its fuse f_2, switch S_2, and a high non-inductive resistance R_1 across the mains for voltages up to 250. R_1 is adjusted to give a round number of volts per mm. deflection on the scale. The synchronous motor for rotating the mirror is connected in series with a non-inductive resistance across the mains as shown. For voltages up to 15,000 a small transformer is used with the motor, and there is a slight modification in the connections of the P.D. loop with resistances across the mains.

Potentiometer Standard Measuring Instruments.—Of the various types of measuring instruments designed for use as standards in the calibration of ordinary instruments, the so-called potentiometer must rank as one of the best. It possesses many advantages, enabling extremely accurate measurements to be made of *resistance*, *current*, *voltage*, and *electrical power* with ease and rapidity. As is suggested by the name, the potentiometer is a potential measuring instrument, all readings being in terms of a universal standard of E.M.F., *e.g.* the Clark cell or its modifications.

There are several forms of potentiometer, now in common use, which have been devised by different makers, but the description of one well-known prominent form, namely, the *Direct-Reading Potentiometer*, made by Messrs. Elliott Brothers, of London, will suffice here. A general view of the instrument is shown in Fig. 111, and a diagrammatic view in Fig. 112. It consists of a wire resistance RRR accurately divided into 149 sections, each about 3 inches long,

FIG. 111.—Direct-Reading Potentiometer (Elliott Brothers).

and connected to fixed contact studs shown, numbered 1, 2, 3, . . ., etc., up to 149 in Fig. 112.

The resistance RRR terminates at one end in a very short 'slide-wire' KM, over which moves a scale arm L. This is provided with a spring contact key W, which when depressed makes contact with any point on KM corresponding to the position of L on the scale. The 149 sections, together with the slide-wire KM, are all adjusted so as to be absolutely equal to one another in resistance. Inequalities in the 'drawing' of KM are compensated for by dividing the scale over which L moves, so that the individual divisions of RRR are exactly multiples of those on the scale. For example, the P.D. over 140·7 sections of RRR is exactly five times that over 28 divisions of KM and 14 divisions of the scale. The divided wire resistance RRR with

its contact studs is arranged in circular form, and concentric with a large toothed wheel.

At one extremity of this wire N—at the 149th contact—it is connected to a small fine-adjustment rheostat O, and then to P and Q, two other adjustable rheostats in series, and so proportioned that the total resistance value of O is rather greater than that of one section of P, whilst the total value of all the sections of P is slightly greater than that of one section of Q. P, Q, and O are not adjusted in any definite values—they serve simply as adjustments. In practice the whole of Q, P, and O are approximately 200 ohms altogether. The divided wire RRR itself is about 30 ohms resistance, and one end of rheostat Q is joined to terminal B. The other extremity of the wire RRR is taken up through the top of the instrument at K, where it is led round a curved segment, and where the moving contact arm L can travel over it. A scale is fixed to the top of the instrument, and a pointer is attached to L, so that when the moving contact is on the stud K, the pointer attached to the arm L stands at zero on the scale. When the arm L is moved till the pointer stands at the figure 10, then the moving contact has passed over a length of the divided wire exactly equal in resistance to any of the other 149 sections between K and N.

A contact J can travel round the circle of the divided wire and make contact with any of the 149 small contacts fixed to it. This contact J is attached to a large toothed wheel, the edges of which can be seen in Fig. 111 on the right and left of the instrument. This affords a ready means of shifting the position of contact J, and its position with reference to N and K can be seen through a small window in the front of the instrument, through which a number shows corresponding to the number of the contact on which J lies; a device is provided to cause J to make contact definitely on either one or other of any pair of adjacent contact studs on the divided wire. A wire is led from J to one on the galvanometer terminals E.

The travelling contact on arm L is connected through a small key W to the bar of the multiple switch, the other bar H being connected to the second galvanometer terminal D. The key is provided with a small clamping device, so that it can be kept down if desired, and the galvanometer deflections manipulated with key X. Care must be taken that no source of E.M.F. is attached by mistake to terminals F, G, etc., as, in the event of key W being clamped down and switch V being in these terminals, a comparatively powerful current might flow through the galvanometer and the slide-wire, probably damaging both. The key K therefore should only be clamped down when

making a series of tests in which there is no chance of a wrong connection having been made outside the instrument.

It will be seen that a closed circuit always exists between A and B, *i.e.* from A through C to M, K, RRR, N, O, P, Q, etc., to B, through which the current from the working cell passes. This circuit is of variable resistance owing to it containing the variable rheostats O, P, and Q; but in all cases the whole of the divided wire RRR is in circuit. The working battery, consisting of one secondary cell, is connected to the terminals A and B in all measurements, a small fuse being inserted at C to protect the slide-wire from injury should too high an E.M.F. be accidentally applied to A and B. The galvanometer, which should always be of the D'Arsonval type (p. 211), is connected to terminals D and E, across which latter is connected a short-circuit key X. This key in its free position keeps the galvanometer short-circuited and thus protected against being deflected. A multiple double-pole switch V enables the two common bars H and I to be connected to any of the pairs of terminals FG, F_1G_1, F_2G_2, etc., at will. Across these pairs of terminals respectively are connected the various sources of P.D. to be compared or measured.

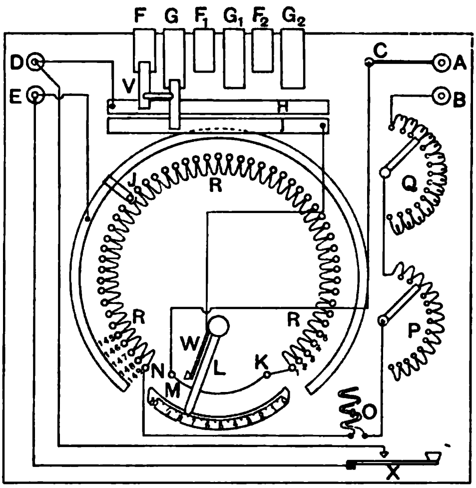


FIG. 112.—Diagram of Potentiometer.

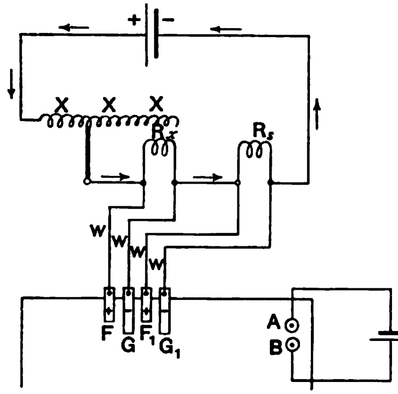


FIG. 113.—Measurement of Resistance.

Having now described the potentiometer itself, it may be well to briefly indicate the mode of using it for the various measurements. Having connected the galvanometer to DE, the working cell of the potentiometer to AB, and the *standard cell* (of known E.M.F.) in series

with a high resistance to the terminals F, G, the first operation is to '*set*' the potentiometer, except in the measurement of resistance only, when it is unnecessary, as also is the use of the standard cell.

Let the E.M.F. of the standard cell (corrected for temperature) be 1·4340 volt, then set the figure 143 at the window and the arm L to 4·0 on the scale. With the multiple switch V to terminals F, G, vary P, Q, and O so that on pressing the key W no deflection is obtained on the galvanometer. The P.D. down the divided wire, etc., is now just balanced by the E.M.F. of the standard cell, and is equal to it; hence each movement of the toothed wheel corresponds to 0·01 volt, and that of the arm L from 1 to 2 or 2 to 3 on the scale means 0·001 volt. The variable rheostats P, Q, and O must not on any account be touched now except to maintain the true 'setting' of the potentiometer, should it alter slightly from time to time. Suppose now that we require the value of a resistance R_x, then a standard known resistance R_s is chosen, having a value as near to that which R_x is thought to have as possible. These two are joined up in series with an adjustable rheostat XXX and a secondary battery (as shown in Fig. 113) capable of supplying a *constant current* through them. The terminals of R_x and R_s are connected to the potentiometer at FG, F_1G_1, . . ., etc., by wires W.

A steady, constant current C of suitable value, but which must not exceed a value that will make CR_x or CR_s greater than 1·5 volt, is now maintained through R_x and R_s, and the terminal P.D. across each successively measured by adjusting the window and slide-wire readings so that on pressing the key no deflection is obtained on the galvanometer.

Then $$PD_x : PD_s = R_x : R_s \quad (\textit{vide } \text{p. } 68).$$

To measure current, only R_s is needed, which should in all cases have such a resistance that if multiplied by the maximum current to be used the product does not exceed 1·5 volt. Having '*set*' the potentiometer, measure the P.D. (V_s) across R_s (Fig. 114) for any current to be determined. Whence by Ohm's Law we have the current

$$C_s = \frac{V_s}{R_s} \text{ amperes.}$$

In the measurement of E.M.F.'s any value up to 1·5 volt can be connected directly to the potentiometer and measured. All P.D.'s greater than 1·5 must be connected to a ratio box consisting of a subdivided resistance (Fig. 115). If then the potentiometer be connected across a known fraction R_f of the total resistance R_T to which the whole P.D. V_T is joined, it will measure the same fraction, namely,

$$V_r = \frac{R_r}{R_T} . V_T \text{ volts},$$

which must not exceed 1·5 volt.

For greater detail with regard to making measurements with the potentiometer, the reader can more appropriately be referred to books dealing with the practical side of the subject only.

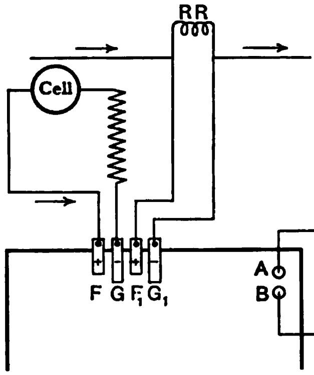


FIG. 114.—Measurement of Current.

Moving Soft-Iron Needle Ammeters and Voltmeters.—This type of instrument forms a large class at the present day, and comprises all those instruments in which a light piece of very soft iron, free to move, is attracted or repelled under the influence of an electro-magnetic field set up by a suitably wound solenoid. There are many forms of instrument working on this principle, each manufacturer employing either a different shape of needle or form of motion of this so-called moving piece of soft iron.

A little consideration will make it apparent to the reader that since the strength of a magnetic field depends on the *ampere turns* of magnetising force (*vide* p. 131), it is immaterial whether this product is given by a small current through many turns of fine wire or by a large current through a few turns of thick wire, for the *same size of coil*, and *same strength of field* so produced. Consequently the only difference between an ammeter and a voltmeter of this type lies in the winding of the working coil, and in nothing else. For example, an ammeter, which measures current strength, is connected in series with one main, and should have as small a resistance as possible. It is wound with a few turns of insulated copper wire sufficiently thick to carry the main current without any appreciable loss of pressure in the coil.

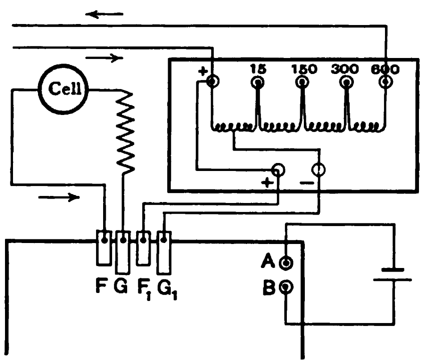


FIG. 115.—Measurement of E.M.F.

A voltmeter, which measures pressure, and should have as high a

resistance as possible, on the contrary, is wound with a large number of turns of insulated thin copper wire so as to pass as little current as possible, for a voltmeter is connected across the two supply mains. The controlling force, tending to restrain the deflection of the needle, with its attached pointer, from zero, may be either *gravity*, that due to *a spring*, or that due to a *permanent steel magnet*. This type of instrument is applicable to the measurement of alternating current and pressure, and is simple in construction. All forms of the moving-needle type of instrument have the disadvantage that, unless shielded (*vide* p. 9), they are liable to read wrongly through being affected by magnetic fields due to neighbouring magnets or currents flowing in neighbouring wires. For this reason such disturbing elements should be kept as far away from these instruments as possible.

We may now consider some particular form or make of electromagnetic instrument of the moving soft-iron needle type. In selecting one for description the author has chosen that known as the *Vulcan standard moving-needle* form in being as representative of the principle as any other form. The working principle will be understood from Fig. 116, while Fig. 117 is the general view of a voltmeter with a 10″ dial reading from 0 to 150 volts. It consists of a short brass tube T terminating in brass flanges F, F, the bobbin thus formed being wound with either thin or thick insulated copper wire as desired. A very soft piece of iron wire NS, about No. 14 gauge, lies between the winding and tube T and extends the whole length between the flanges. A light steel spindle AA is pivoted in jewelled centres which are carried by a brass cross-piece B at the front end and another at the back.

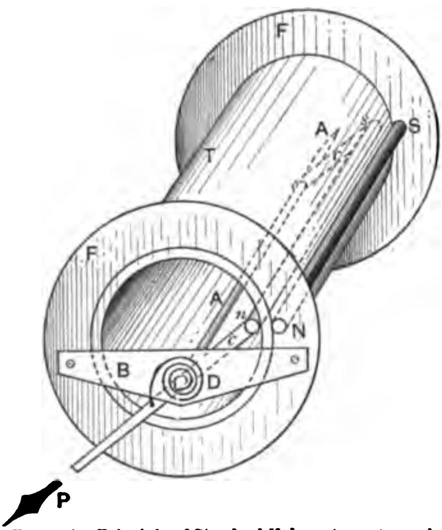


FIG. 116.—Principle of Standard Vulcan Ammeter and Voltmeter.

To this spindle is fixed the light aluminium pointer P and two light arms *c*, *c* of the same material, which carry another piece of soft-iron wire *ns* about as long as NS. In the zero position of the pointer P which the hair-spring D of phosphor bronze tends to maintain, the wires *ns* and NS are parallel and close together, one either side of the

wall of the tube T. When therefore a current traverses the coil both wires become magnetised, similar polarity being set up at the same end. Hence the movable wire is repelled a certain distance from the fixed wire, corresponding to the strength of current flowing. This the pointer P therefore indicates on the scale, and it comes to rest when the deflecting force of the current balances the restraining force exerted by the spring D. In this and all similar instruments the amount of iron in the moving needle and about the instrument generally is reduced to

FIG. 117.—Vulcan Voltmeter.

a minimum, particularly when it is for use with alternating currents. Further, the iron is of the softest obtainable, so that the residual magnetism and hysteresis exhibited by it may be as small as possible.

Moving-Coil Permanent-Magnet Ammeters and Voltmeters.—The various makes of instrument belonging to this type, though differing somewhat in details of construction, all work on one common principle. This perhaps will the more easily be understood by the description of one of the latest forms which has been devised, and is made by Messrs. Crompton and Co., of Chelmsford. Referring to a plan and elevation of the working parts of the instrument, shown in Fig. 118, in which some details (to be seen in subsequent illustrations) have been omitted for the sake of clearness, it consists of a powerful U-shaped permanent magnet M, specially treated, or 'aged,' as it is termed, to ensure that its strength (*i.e.* its magnetic

moment) shall remain practically constant with time after the instrument is once made. The poles N and S of M are both bridged and fixed by means of the screws A to a compound piece consisting of soft-iron cheeks I fitted with brass spacers and holders B into what has the appearance (except under close inspection) of a solid block with a central cylindrical hole T accurately bored. This compound block is shown to the left of Fig. 119, and is provided with four lugs L for screwing it down to a base.

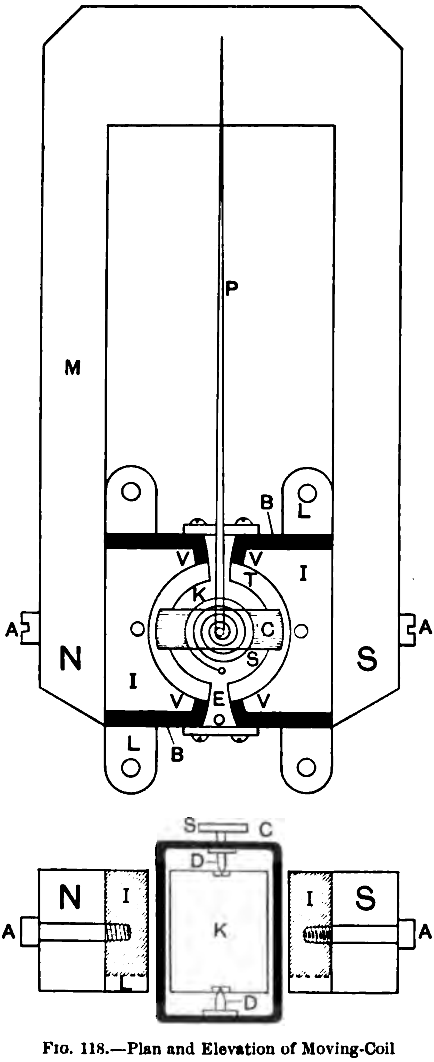


FIG. 118.—Plan and Elevation of Moving-Coil Permanent-Magnetic Instrument.

The tips V of the soft-iron cheeks I, which, by direct contact with the limbs of M, form curved magnetic poles of north and south polarity, are separated by the non-magnetic brass of the spacers B. These last-named support rigidly, by means of a brass disc provided with two projections E, a cylindrical soft-iron keeper K of the same diameter, concentrically with the hole T.

Pivoted by steel points D resting in jewelled centres, which are let into the ends of K, is a light rectangular coil C. This consists of a large number of turns of fine insulated copper wire, wound on a rectangular frame made from a strip of aluminium foil, so that a dead-beat motion of the moving coil is obtained (*vide* p. 194). To the upper pivot is rigidly attached a very light aluminium pointer P for indicating the motion of the coil C; and a delicate spiral phosphor bronze hair-spring S, one end of which is fastened to D, and the other to a

ring with a milled edge (Figs. 119 to 121), serves as the controlling force of C, tending to keep it in its zero position. By slightly turning the milled ring the pointer P can at once be set to zero on the scale if it ever becomes displaced. The moving coil C, the keeper K, attachments, and connections can be removed from the block in one piece as shown in Fig. 119. The top view of the block with the movable system in position is shown in Fig. 120, and the bottom view in Fig. 121. The current is led into and out of the moving coil by two very thin curved flexible ligaments, seen in Fig. 121, and not by the usual hair-springs employed in all other forms of moving-coil permanent-magnet instrument.

A complete instrument of this make is shown in Fig. 122, mounted in an iron case in order to shield it magnetically. The moving-coil type in general can be made to measure voltages of any magnitude by connecting the moving coil in series

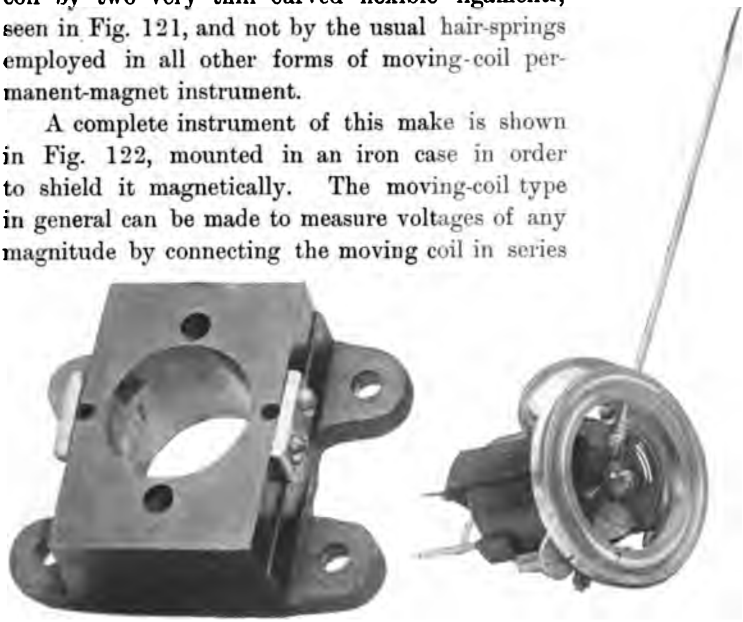


FIG. 119.—Pole-Pieces and Moving Coil.

with an extra non-inductively wound high resistance made of low temperature coefficient material, the extremities of the combination being the terminals of the voltmeter (*vide* p. 74). An ammeter is formed by connecting the coil in series with a small resistance to the ends of a low-resistance shunt which is capable of carrying the full current easily. The scale is then graduated in amperes by comparing the deflections of the pointer with those of an accurate standard ammeter. The principle of action of this type of instrument is identical with that described on page 211 *et seq.*; but in this case, owing to the pole-pieces and keeper being very close together, and to them being turned accurately concentric, the magnetic lines of force are everywhere uniformly distributed in the gap, so that the deflecting force, due to

a current in the moving coil, is directly proportional to the current. Thus a uniform scale of equal divisions from end to end is obtained.

FIG. 120.—Moving Coil in Position between Poles.

Since a permanent magnetic field is used, this type of instrument can only be used with continuous current and will not work with alternating currents.

A particularly clear view of the working parts of another form of permanent-magnet moving-coil instrument is shown in Fig. 123. It is made by Dr. Rudolf Franke and Co., of Hanover, and part of one magnet pole is removed in order to show the moving coil and keeper, etc., more clearly. It will be seen that the moving coil is pivoted to a cross-bar at the top and bottom instead of to the keeper as in the Crompton form.

An important advantage, common to all the different forms of this class of instrument, lies in the fact that, owing to the strength and compactness of the permanent magnet, these instruments are practically unaffected by external magnets and magnetic fields set up by currents flowing in neighbouring wires, etc.

'Hot-Wire' Ammeters and Voltmeters.—The thermal or heating property of an electric current, mentioned on page 35, has been in the past, and still is, being employed to a very considerable extent in the manufacture of instruments for measuring current and pressure. All such instruments utilise the property in the same way, namely, in the heating of a *stretched wire*; but different makers employ different devices for magnifying and indicating the expansion or elongation of the *hot wire*, which is made to serve as an indication of the current flowing through it.

As is well known, Major Cardew was the first to devise a practical form of instrument working on the thermal principle, after spending

a vast amount of labour in overcoming several sources of error inherent with this kind of instrument. Acting on the experience gained in the evolution of the Cardew form, other makers have sought to

FIG. 121.—Under Side of Pole-Piece and Coil.

utilise the same principle in a more compact form, and by eliminating errors in other ways. Before describing a prominent form of hot-wire instrument, it may be well to briefly consider the theory of the principle. From principles laid down on page 54, the reader will at

FIG. 122.—Crompton Moving-Coil Voltmeter.

once see that, if a current of C amperes flows for t seconds through a wire of R ohms resistance, the P.D. between its extremities being V volts, the total number of heat units H generated in the wire will be

$$H = 0{\cdot}239C^2Rt = 0{\cdot}239VCt.$$

The unit of heat adopted was defined on page 54, and if W is the weight of the wire in grammes, S the specific heat of the material of the wire, which may be defined as the quantity of heat absorbed by it, for a given rise of temperature, compared with the quantity of heat absorbed by an equal mass of water when raised through the same range of temperature, and if T° be the rise of temperature, then we have

$$T^\circ C = 0{\cdot}239\,\frac{C^2Rt}{WS} = 0{\cdot}239\,\frac{V^2t}{RWS}.$$

Now when a current is sent through the wire, the latter is heated,

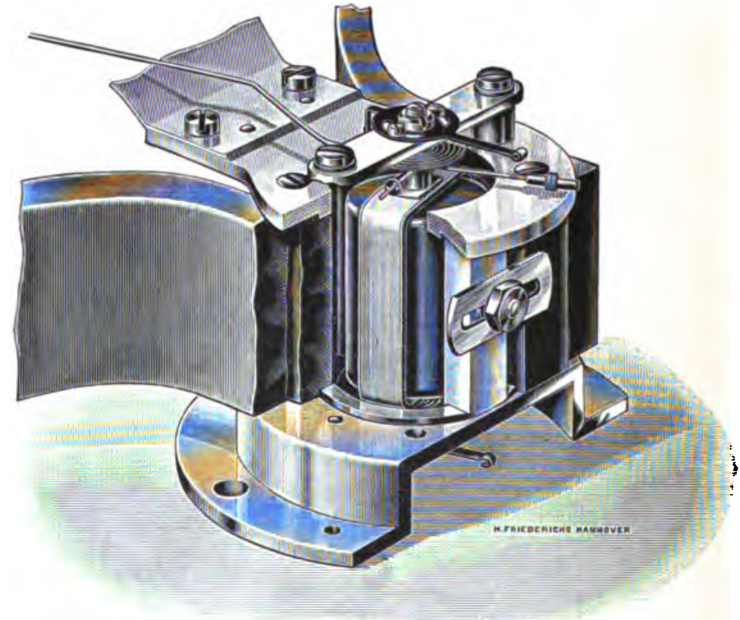


FIG. 123.—Moving-Coil Instrument.

and the linear expansion or elongation of the wire is proportional to the product of the rise of temperature T° and the coefficient of linear expansion *a* for the material of the wire, *i.e.* the elongation is proportional to T°.

But the rise in temperature only goes on until the rate of production of heat due to the current is balanced by the rate of loss of heat by radiation, and which latter is nearly proportional to the rise of temperature T°. Hence the expansion or elongation of the wire is proportional to C^2 or to V^2, where W and S are constants and R nearly so for a given wire, this consisting of a material which changes very little in resistance with the change of temperature experienced by the wire in a 'hot-wire' instrument.

We may now describe the *Vulcan hot-wire instrument* supplied by Messrs. Geipel and Lange, of London, and which is one of the latest forms of the direct-reading thermal type. The general arrangement of the working parts is shown in Fig. 124. The working hot wire A, composed of low temperature coefficient material, usually the alloy platinum-silver, is fixed at one end to a horizontal bar M pivoted at D, while its lower end is fixed to one end of a shorter horizontal bar L. This bar L is pivoted at E to a bracket O, its other end being suspended by a fine wire W which passes round a small pulley K (capable of turning on a small spindle running in jewelled centres) and is attached to the lower end of a spring H fixed to a bracket G. To the spindle carrying K is rigidly attached a light pointer P (with its balance weight R), which moves over the scale S. A constant tension is kept on the working wire A by means of the adjusting nut N and spring C.

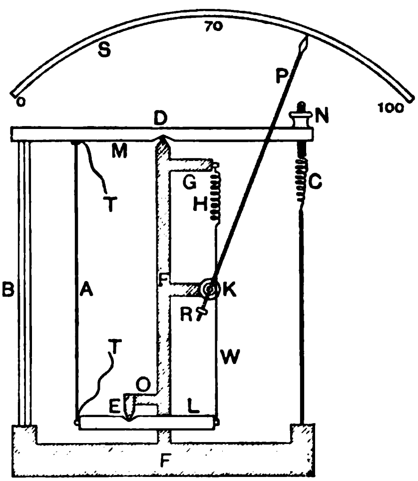


FIG. 124.—Principle of Vulcan Hot-Wire Instruments.

When a current is sent through A, the wire extends, due to heating, and the extension is at once taken up by the tension of the spring H which pulls up the wire W, and with it the lever L, which tilts about the pivot E. The upward motion of W which passes round K causes this latter to turn, and P to take up a position on S corresponding to the elongation of A. The effect of external changes of temperature is nullified by an ingenious compensating device as follows :—A number of wires B, having the same coefficient of expansion as A, are fixed at the bottom end to the frame F, so that any elongation must be taken up at the top end. They are kept taut by the spring C, which actuates the upper end of A as well.

The wires B and A, therefore, elongate by the same amount for any external change of temperature, which, however, only affects the top ends. Consequently the lower end of A which actuates P maintains the same position in space for any *external change of temperature.* Any slight alteration of zero with time is readjusted by turning the nut N so as to increase or diminish the tension of C. The ends of A are connected by wires T, T to the terminals of the meter.

These instruments are particularly economical in power wasted or required to work them as compared with the hot-wire type generally, voltmeters requiring only 0·1 ampere through the wire A to give a full-scale deflection, while other forms take from 0·2 to 0·35 ampere. The working parts of the instrument are the same for both ammeters and voltmeters.

The instrument becomes an ammeter by shunting it for all currents

FIG. 125.—Vulcan Hot-Wire Ammeter.

above 4 amperes to a low-resistance strip, or shunt as it is often termed, and which carries practically all the current with a fall of pressure between its terminals of 0·15 volt for a maximum scale deflection. This fall of potential in other forms varies from 0·2 to 0·3 volt. Fig. 125 shows the arrangement and indicates an instrument with a 7″ dial connected to a 1000-ampere low-resistance shunt seen above it. A voltmeter has the same appearance, but instead of the shunt it is placed in series with a high non-inductive resistance which does not vary with change of temperature. The magnitude of this resistance, which up to 150 volts is placed inside the instrument, determines the maximum voltage which the voltmeter

will measure. Thus it will be seen that the thermal principle can be utilised for the measurement of both current and pressure, but owing to this and all other similar instruments operating under the *square law*, the scales of all are crowded near zero and gradually open out. Readings can only be taken at all accurately on three-fourths of the scale, while the last one-third of the whole range occupies the last half of the scale.

Hot-wire instruments have the following advantages over those working on the electro-magnetic principle, namely, they are (*a*) dead-beat; (*b*) direct reading; (*c*) unaffected by external magnetic fields; (*d*) free from temperature errors; (*e*) they will measure with equal accuracy, on the same scale, both continuous and alternating P.D.'s.

Electro-static Voltmeters.—The reader will doubtless remember (*vide* p. 25) the laws of attraction and repulsion between charges or quantities of electricity, namely, that those of *like sign repel*, while those of *opposite sign attract*, one another. It will, therefore, be evident that two conductors in fairly close proximity to, but insulated from one another, will tend to attract one another if they are charged, one with $+^{ve}$ and the other with $-^{ve}$ electricity, or which is the same thing, if they are connected to the terminals of an electric generator. Further, if one of these conductors be free to move very easily, it will be attracted to and move towards the other fixed conductor; the greater the charge on each, or the P.D. between them, the nearer will it approach to the fixed conductor for the same restraining force. The foregoing principle of electro-static attraction between two bodies charged to opposite potentials forms the basis of the action of the most important class of potential measuring instruments known commercially as the electro-static voltmeter, or physically as the electrometer.

There are different forms of electro-static voltmeters as made by different manufacturers, but the principle is precisely the same in them all. We will, therefore, confine ourselves now with the description of one form, namely, the *Ayrton and Mather electro-static voltmeter*. The construction will be understood from a reference to Fig. 126, which is a perspective elevation, and to Fig. 127, a plan of the principal parts. It consists of two outer vertical brass plates, G, G, curved into the form of nearly quarter cylinders which are held together rigidly by the brass end-pieces L, L, the lower one of which terminates in the plates M, M for screwing the arrangement to a base. Carried by, and in electrical connection with, G, G are two inner curved brass plates H, only the left-hand one being visible in Fig. 126. These plates H are also nearly quarter cylinders, con-

centric with but rather shorter than G, G, a narrow cylindrical air-gap being left between H and G.

A very light frame of aluminium foil, consisting of two curved side pieces N (forming nearly quarter cylinders), held together rigidly at the top and bottom by strips R of foil, is carried by a vertical steel spindle E, pivoted in jewelled centres, which are fixed in insulating collars carried in L, L. The motion of the so-called needle N is indicated by a very light aluminium pointer P fixed to E, and is controlled by a fine phosphor bronze hair-spring K. The inner end of K is fixed to E, and the outer end to a tension-adjusting arm A (Fig. 127), by slightly turning which the pointer P can be adjusted to zero on the scale S. P is counter-balanced by an extension or weight on the opposite side of the spindle E. The curved sides N of the movable needle are concentric with those of G and H, and can move in the air-gap between these fixed sides, which are sometimes termed '*inductors.*'

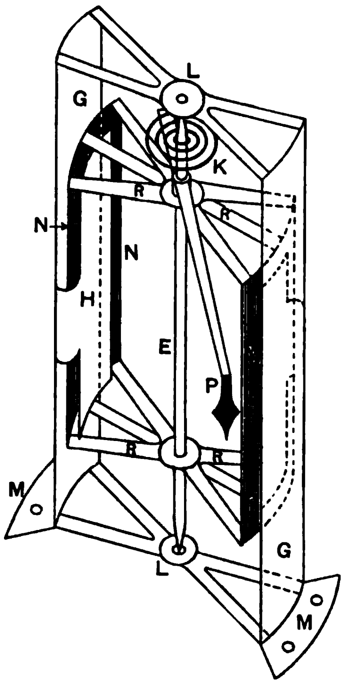


FIG. 126.—Principle of Electro-static Voltmeter (Ayrton and Mather's).

The connections in the instruments are shown in Fig. 127, the fixed inductors being in electric connection with one terminal of the instrument through a fuse F, the needle N and the other parts of the instrument being connected to the other terminal through another fuse F. The instrument is protected from damage in the event of a discharge taking place between N and GH (Fig. 126) by very fine fuses F, F, consisting of platinum-silver wire, one mil (0·001 inch) in diameter, kept taut inside a glass tube by a spring D. These tubes are provided with brass caps C, which make connection with each other through D and F. Highly insulated terminals make connection with N and G (Fig. 126) by being pressed against the caps C at one end of the fuse tubes, and by (in turn) pressing the caps C at the other ends of these tubes against the springs B, which are in contact with the working parts through the wires shown in Fig. 127. A photo of the interior of one of these instruments, reading from 200 to 600 volts, with cover removed, is shown in Fig. 128. In this can be seen

the two wires connecting the left-hand ends of the springs B (Fig. 127) on to G, and the other through the spring K to the moving needle N.

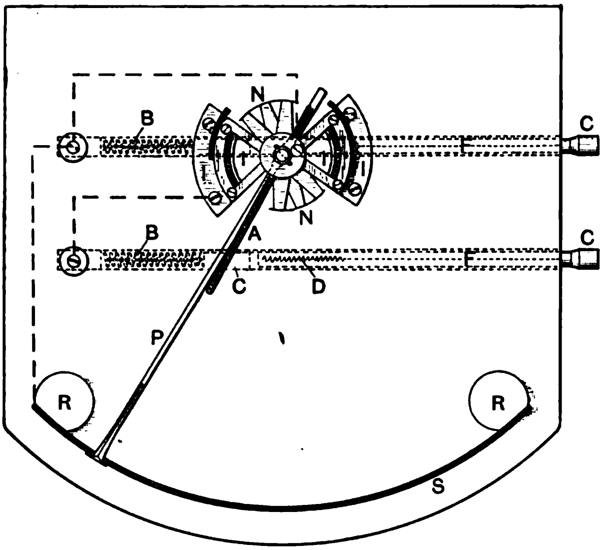


FIG. 127.—Plan of Electro-static Voltmeter.

The projecting fuse tubes can be seen to the right of the base, while the brass terminals encased in ebonite which press against these are seen in Fig. 129, which is the general view of one of the latest forms (reading from 40 to 130 volts) of Ayrton and Mather's

FIG. 128.—Interior of Electro-static Voltmeter.

station type electro-static voltmeter. The instrument is practically dead-beat in its action without any special damping arrangement, owing to the extreme lightness (less than 25 grains) of the moving system, and it is also free from creeping errors. The working parts are all highly

insulated and shielded from the injurious effects due to external electrification by being enclosed in a metal case (*vide* p. 24).

The action of this and all other forms of electro-static voltmeters is as follows:—The movable needle N being just outside the fixed quadrants GH for the zero position of the pointer P, then on applying a P.D. to the terminals of the instrument the fixed and moving portions become oppositely charged, and the latter is attracted (against the controlling force) into the space between the fixed quadrants by an amount which increases as the P.D. applied increases. Thus

FIG. 129.—Electro-static Voltmeter Complete.

we see that the action is such as to tend to make the capacity of the instrument a maximum, and this latter is the case when N is wholly inside GH. Voltmeters of the electro-static type, by reason of their form of construction (*vide* p. 238), possess a very small electro-static capacity, which is rarely greater than about 10^{-6} mfd., and often, as in the present instance, much less.

Such instruments are, therefore, equally accurate when used with either direct or alternating pressure of any rate of reversal. This is a valuable feature, but their scales are not all that one could desire, and are only readable from full-scale deflection down to about one-third to one-fourth of this. A further advantage lies in the fact that they pass no current continuously like a current voltmeter does, and

therefore they cannot affect the P.D. between the points to which they are connected.

Wattmeters.—The practical unit of electrical power, called 'a watt,' was defined on p. 56, and as the name implies, a wattmeter is an instrument which measures electrical power in watts, or multiples thereof, at any particular moment of observation. For continuous currents the employment of such an instrument presents no very special advantages, for it is usually the case that both the current in amperes flowing in the circuit and the P.D. in volts across the circuit are separately measured and noted, when the *true power* absorbed is easily obtained by the product—amperes × volts —which is equal to the watts.

With so-called alternating currents, however, the case is entirely different, for the amperes × volts (except in the very few cases where the circuit is non-inductive) is not equal to the *true power* in watts. The reason of this cannot be discussed at the present stage, but will be explained in detail in a later chapter; suffice it to say now that the true power can only be measured directly by a wattmeter. The value of this type of instrument to the electrical engineer can therefore hardly be over-estimated.

The general principles involved in the construction and action of a wattmeter will be understood by the reader in the description of a well-known form made by Messrs. Hartmann and Braun, of Frankfort, and supplied by Messrs. Moul and Co., of London.

This wattmeter works on the electro-dynamometer principle of a fixed current coil acting on a moving pressure coil. It consists (Fig. 130) of a fixed main coil M which carries the main current, and is composed of a number of turns of a strand of one or more *thin* copper strips (about ½″ wide). These are connected in parallel to eliminate eddy currents which would otherwise be set up in a strip of considerable thickness. The ends T, T of the main coil M are joined to the two terminals to be connected up in series with the main circuit. The moving pressure coil C is composed of a considerable number of turns of fine copper wire, silk-covered, and wound primarily on a rectangular 'former' which is afterwards removed. The coil C is mounted on a hardened steel arbor A or spindle, which is pivoted in jewelled centres (only one (H) of which is shown) and carries the pointer P, a damping disc at the end of the extension F, and two phosphor bronze spiral hair-springs E and D, which not only serve to lead the pressure current into and out of the moving coil C, but also act as a torsional controlling force. The damping device for producing a dead-beat motion of the moving system consists of a light vane, carried by the extension F of the

pointer, and moving freely in a close-fitting curved air-box B with closed ends. The cushioning of the air inside B as P and F move gives the requisite damping to their motion.

The moving coil itself has a resistance of about 100 ohms, a coefficient of self-induction of about 0·0072 heavy, and a maximum current-carrying capacity of 0·05 ampere. It is thus capable of only standing a pressure of 5 volts at its terminals. In order to be able to use it, and therefore the wattmeter on much higher pressures, it is connected in series with a high resistance wound with wire of a practically negligible temperature coefficient. This extra resistance is carefully wound with double-silk-covered wire, in thin layers, on highly insulated frames. It is then thoroughly dried at high temperature and varnished, especial care being taken to eliminate, as far as possible, any capacity effect.

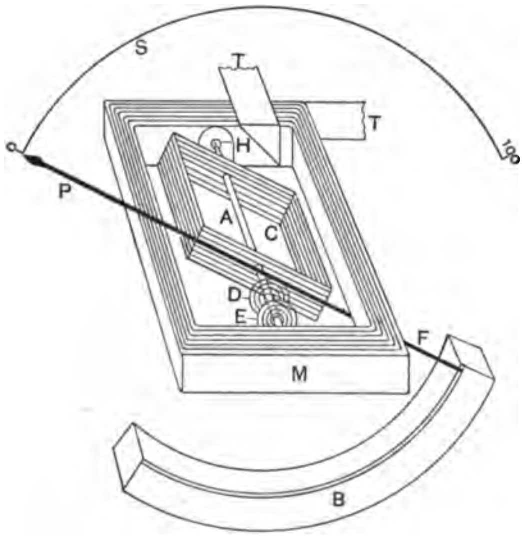


FIG. 130.—Principle of Hartmann and Braun Wattmeter.

In a portable form of this instrument for 20 amperes and 100 volts, the moving coil was about $\frac{1}{16}''$ thick and $\frac{3}{8}''$ wide (axially), the total resistance of its circuit, including its extra series resistance, being 3300 ohms. The fixed thick coil was wound with about 40 or 50 turns of thin copper strip about $\frac{1}{2}''$ wide, the total width of the turns, including the insulation between them, being about $1''$ and their resistance 0·0082 ohm. The scale S consisted of 100 equal divisions each corresponding to 20 watts, but this constant of 20 will vary in different instruments depending on the number of ampere turns produced by the two coils. A general view of a wattmeter of this make is shown in Fig. 131. The action of the wattmeter will be readily understood from the principle stated on p. 212, for if the lines of magnetic force, due to the main current passing in M, flow in one direction through the coil, and a current is sent through the moving coil C, such that the lines of force due to it flow in a nearly

opposite direction, then C will turn so as to tend to make the two magnetic fields coincide in direction through both coils together. Now the mutual torque between M and C, or the deflecting force acting on C, is proportional to the ampere turns of M × the ampere turns of C, *i.e.* to the current in M × the current in C, and the current in C is proportional to the voltage. Therefore the deflecting force is proportional to the product CV, *i.e.* to the *watts* expended in the

FIG. 131.—General View of Hartmann and Braun's Wattmeter.

circuit, and the deflection will be steady when the deflecting force due to the watts is just balanced by the controlling force due to the torsion of the springs D and E.

Wattmeters constructed on the above principle belong to what is called the dynamometer type of instrument, and are applicable for measuring electrical power in either continuous or alternating current circuits. Their readings are independent both of the shape or form of variation, and of the rate at which the alternating current repeats itself, or in technical language—of the form of current curve and the

periodicity of the current. Considerable care, however, is necessary in the construction of wattmeters of this type in order that they may read accurately with alternating currents. For instance, the inductance of the fine-wire or pressure circuit must be reduced to a minimum. As little metal-work as possible should be employed about the instrument, in order to avoid induced currents being set up in the same, and further, the temperature coefficient (p. 72) of the fine-wire circuit should be as small as possible.

Another distinctive type of instrument met with in practice is the so-called Rotary Field or *Induction Wattmeter*, and to this must be added the *hot-wire* type of *wattmeter* suggested by Mr. M. B. Field.

For further information, however, the reader must refer to a *work* dealing with this subject by itself.

Recording Instruments.—The various types of ammeters, voltmeters, and wattmeters for the measurement of current, pressure, and power, which have been described in the preceding pages, merely indicate the momentary value of the thing measured. By combining them with a little additional mechanism, however, they can be converted into a different class of instrument, commonly termed a *recording*-ammeter, -voltmeter, or -wattmeter, as the case may be. Such instruments give a permanent record of the magnitude of what is being measured at any time throughout a certain period, such as twenty-four hours or longer. As in the case of the former type of instrument referred to above, and from which they are derived, there are as many different forms working on one or other of the principles mentioned on page 35 as there are manufacturers who make them.

We shall therefore consider only one form of recording instrument, selected out of many other equally good forms, as serving to illustrate most easily the additional items in the construction of a recorder. Fig. 132 illustrates the internal view of the working parts of a dead-beat moving-coil permanent-magnet recording ammeter supplied by Messrs. H. M. Salmony and Co., of London. The upper portion, combined with the low-resistance shunt at the bottom, constitutes an ordinary ammeter of the same type and principle of construction as that described on page 230, though not of the same make.

An adjustable scale, graduated in amperes, is carried by two brass arms supported from the magnet, and enables the instrument to be used, if desired, as a direct-reading ammeter.

The extra mechanism necessary to convert the ammeter into a recorder comprises a light cylinder or drum, driven at a desired speed by clockwork inside it. Against the paper chart or scale wrapped round this drum presses the ink-pen carried at the end of the pointer.

In the earlier forms of recording instrument the inking pen has given considerable trouble, owing partly to the pen becoming clogged with use, and to the very light pressure of it on the paper necessary to minimise friction and obtain an accurate record with the small deflecting force available.

FIG. 132.—Moving-Coil Recording Ammeter.

Of late, however, many improvements have been made, and each maker has a different type of pen. That employed in the instrument under description consists of a revolving printing disc formed from two discs mounted on the same axis and pivoted in jewelled centres. The two discs carry between them a recipient of porous material, which allows the ink to pass to their edges, and thus on to the paper chart in the requisite quantity. This disc pen is carried at the end of the pointer made of aluminium tube, whilst the porous material between the discs is continually moistened by ink passing through the pointer from a small reservoir which actually carries the pointer. This can be seen in Fig. 132, just above the spiral hair-spring. This form of marking arrangement has the advantage of very little friction and of being, to a certain extent, independent of the roughness of the paper, owing to the motion being one of rolling and not rubbing. The ink reservoir will contain a supply of ink sufficient for

eight days, while the clock, which drives the drum through one complete revolution every twenty-four hours, will also run for eight days with one winding.

Speaking generally, the clocks of recorders usually have a well-made lever movement, and are capable of being accurately regulated. They should preferably drive the drum through a friction coupling, which prevents the movement being strained. Recorders can be arranged for single-revolution charts, or with continuous runs of paper 65 feet long, thus giving a record in one length extending over a month or less according to the paper speed. This last-named is in some cases $\frac{9}{16}''$, 1″, and 2″ per hour, and for special short-time records $\frac{7}{16}''$ per minute, giving one revolution in 24, 12, 6, and ½ hours respectively. Some makers provide for a rate of 6″ per minute, but 1″ per hour is the usual rate. With long runs the paper is unwound from a spool by the clock drum, either being wound on this or paid into a receptacle provided for it.

The foregoing description will serve to show that almost any kind of instrument can be converted into a recording one by the addition of the marker and revolving drum. By means of such instruments a permanent record in the form of a curve is obtained, and the value of the current, pressure, or power at any particular instant on any day obtained.

Electricity Supply Meters.—In the foregoing pages certain instruments for measuring or indicating pressure, current, and power at any moment, or the fluctuation of such during a given period, have been described. We have, however, yet to deal with another extremely important class of instrument, namely, one for measuring the total *quantity of electricity* or total *amount of electrical energy* given to or absorbed by an electric circuit. Such an instrument is briefly termed an 'electricity meter,' or, bearing in mind the definition of quantity and energy given on pages 39 and 58, it is called an 'integrating coulomb-meter' or 'integrating wattmeter.' This type of meter only indicates the total amount used, and gives no indication of the value of the current or power in the circuit at any particular moment.

The evolution of successful electricity meters has occupied many years, and has accompanied the growth of electric lighting. It is, however, more especially during the last few years that particular attention has been given to this class of instrument, which, no doubt, is in a large measure due to the fact being realised, that the revenue of an electricity supply undertaking is as much dependent on the accuracy of the meter and the system on which current is sold, as on the efficiency of the generating plant and the care with which the system of dis-

tribution is designed. Electricity meters in use at the present day are dependent for their action on one or other of the properties of an electric current mentioned on page 35, those actually employed being the *chemical* and *electro-magnetic* properties.

Chemical meters were the first to be introduced, and have since been perfected, but they can only be used with direct currents. On the other hand, electro-magnetic meters form by far the largest class, and can be made to work with alternating as well as with direct currents. It is to this class that we shall direct our attention in the following pages, but space will not permit of the description of more than two or three representative types.

Electro-magnetic electricity meters may be classified as follows:—

Without clocks: Rotary (motor) and oscillating meters.

With ,, Periodic and continuous-integrating meters.

We will now consider one of the latest types of rotatory or motor meter known as the B.N.R. type 'Eclipse' meter, and supplied by Mr. G. Braulik, of London. The construction will be understood from a reference to the lettered illustration of the meter (with cover removed) shown in Fig. 133, while the electrical circuits are shown diagrammatically in Fig. 134. It consists of a main series or 'field magnet' coil M, as it is termed, wound in a hollow cylindrical form, with insulated copper wire of sufficient size to carry the main current of the circuit. Facing this, and co-axial with it, is another coil S, wound with a large number of turns of fine wire. The moving system, or armature A, as it is called, rotates between the fixed coils M and S, and consists of three oval-shaped coils or loops, wound with fine wire, and fixed to a vertical spindle with their planes at angles of 120° to one another. The light steel spindle is mounted in a jewelled or other nearly frictionless footstep, and carries at the lower end a circular copper disc D, which rotates between the poles of a powerful permanent magnet E. It also carries, just under the armature coils, a small 3-part commutator C, consisting of a short piece of silver tube split axially into three equal parts or segments, which are rigidly attached to the spindle, but insulated from it and from one another. One end of each of the three armature coils H, K, and N (Fig. 134) is electrically connected to one segment, while the remaining ends are joined together as at O. The armature coils, together with the commutator, is thus one of the novel and, at the same time, most important parts of this meter, and, as seen, is of the 'open-coil' type, similar to that used in the well-known Thomson-Houston arc-lighting dynamo. The *pressure* current is led into and out of the rotating armature coils by two fixed light silver

strips or brushes, which press lightly on the commutator as it revolves, and are connected to the two terminals T, mounted on but insulated from the bracket B. The upper portion of the spindle drives the registering gear R, which is really a very delicate revolution counter, the numbers of which spring into sight in succession, thus leaving a record in plain numbers which can be read by any one. The terminals of the meter are shown at 1, 2, and 3 in Figs. 133 and 134.

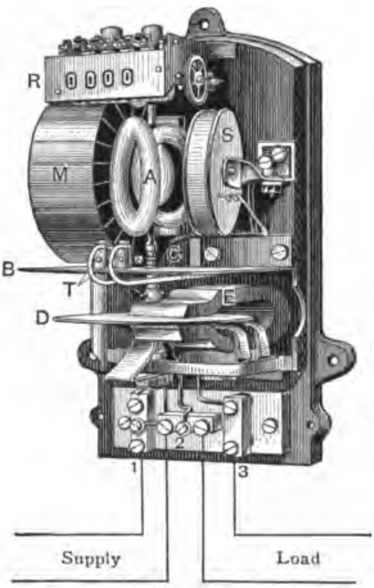


FIG. 133—Eclipse Meter (B.N.R. Type).

The fine-wire coil S is the *shunt* coil of the meter, and is for the purpose of creating an initial magnetic field for overcoming the statical friction of the moving parts when starting, and for regulation at light loads such as $\frac{1}{10}$th full load. At greater loads the 'regulation' or direct proportionality between the readings of the meter and the electrical energy given to the circuit, which it is desired to measure, is obtained by the Foucault brake disc D and magnet E, as will be explained presently. A non-inductive high resistance r is permanently connected in series with the armature and shunt coil for the purpose of reducing the current in this fine-wire circuit to a suitable strength. The resistance r being wound with low temperature coefficient wire enables the temperature coefficient of the whole fine-wire circuit to be reduced to a negligible amount (*vide* p. 72).

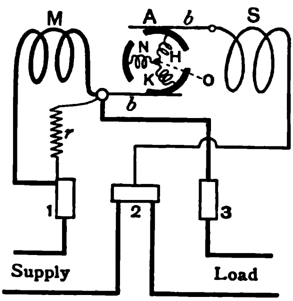


FIG. 134.—Electrical Connection of Eclipse Meter.

In other forms of motor meter constructed on similar principles, the rotating armature usually consists of an 8-part 'drum' or *closed-coil* winding, as it is variously termed, combined with a commutator having an equal number of sections, and each coil carries only one-half the shunt current. With the *open-coil* construction employed in the meter under discussion, however, greater security from a breakdown of the insulation is

obtained owing to the armature coils being connected to the commutator in three places only. Moreover, owing to the copper winding on the moving armature being used to a better advantage, and to the whole winding carrying the full shunt current in this open-coil type, the driving force is from 40 to 70 per cent greater, while the gauge and weight of copper winding is some 40 per cent less, and the sensitiveness therefore much greater. The rubbing friction between commutator and brushes is also reduced to a minimum on account of the former having only three segments, thus allowing its diameter to be reduced to $\frac{1}{4}''$, or about one-half the usual size. The effect of these advantages will be seen in the very small shunt current (only about 0·022 ampere) which flows, and the corresponding loss occurring in the fine-wire circuit. The loss in the copper circuits is only about $2\frac{1}{2}$ watts at full load, or about half that usually met with in this class of meter.

The meter commences to register at about 1 per cent of its full rated capacity, and reads to within $2\frac{1}{2}$ per cent of correctness throughout a range of from 5 to 100 per cent of its rated capacity All iron or other magnetic material has been carefully avoided in the construction of the armature and field coils, consequently the magnetic field due to each is proportional to the current flowing in it. Further, since these fields always occupy the same position relatively to one another, the driving force is proportional to the product of the field strengths, *i.e.* to the product of the armature and series-coil currents, but the former is proportional to the voltage and the latter to that flowing in the mains. Hence the *driving force is* $\propto$ *to volts* $\times$ *amperes* (i.e. *watts*). With, however, the small amount of friction present acting as the only retarding force, even a constant driving force would cause the speed of the armature to increase almost indefinitely. An additional retarding force has therefore to be used, which shall increase proportional to speed, so that the speed may be proportional to driving force, *i.e.* to the watts. This is obtained by the disc D and magnet E, for the Foucault or eddy currents set up by the E.M.F.'s induced in the disc D, of constant ohmic resistance, by its rotation between the poles of the magnet E, create a drag proportional to speed. Hence, at any instant when the driving and retarding forces balance, the speed will be constant and proportional to the watts expended in the circuit.

It will therefore at once be seen that the total number of revolutions is a correct measure of the total electrical energy supplied, and the recording gear will thus represent any desired unit of energy (p. 58). The meter will read accurately on either direct or alternating current circuits of any frequency or power factor.

Alternating Current Electricity Meters.—These, with two or three

exceptions, differ considerably in both construction and working principle from electricity meters intended for use with continuous currents. The exceptions alluded to are those types of meters possessing a moving fine-wire pressure coil, the current through which is led into and out of the coil by flexible connections or rubbing contacts. In such delicate appliances as meters the friction at these contacts, coupled with that at the bearings of the moving system, is liable to and often does introduce errors at light loads when the driving force is small.

The difficulty has, however, in the case of alternating currents been overcome in an altogether novel and modern construction based on a principle first pointed out by Prof. Ferraris some years ago, namely, that motion can be imparted to a solid conductor (free to move) through the currents *induced* in it by a fluctuating external magnetic field. In this way a meter can be made with no electrical connection whatever to the moving system, and no rubbing contact other than that at the jewelled bearings which can be minimised, though not entirely eliminated. Such meters, commonly known as *induction motor meters*, are in great favour at the present day, and will only work with alternating currents. The primary circuit in all of them is fixed, while the secondary (*i.e.* the solid conductor) rotates at a rate directly proportional to the *true power* developed in the primary circuit.

It will suffice here to describe one of the many forms of induction motor meter, namely, the '*Brush Gutmann*,' which is one of the latest and is a true integrating wattmeter. It is made by the Brush Electrical Engineering Company, and the construction will be understood from a reference to Figs. 135 to 139. The line illustration (Fig. 135) is only an approximate representation, so far as the general size, form, and disposition of parts are concerned, of the construction shown by the figures which follow. The moving system of the meter, which weighs only three-fourths of an ounce, consists of a thin aluminium disc D, which may be termed the armature, having spiral slots (as shown in Fig. 136) for the purpose of obtaining the highest possible driving force. This disc is carried on a slender steel spindle E, the lower end of which is turned and polished to a ball-shaped pivot, and rests in a jewelled (sapphire) centre, the upper end being turned to a fine spindle and working in a brass bearing. This latter acts more as a guide than a bearing, and is adjustable vertically by the screw-head P, thereby enabling the moving system to be removed for repairs if damaged.

The upper portion of the spindle E carries a non-tarnishable worm G (Figs. 135 and 136), which drives the recording train of toothed wheels and dials seen in Fig. 138. An aluminium bracket A carries

the centres for the spindle E, and also two thick wire coils M, M, which are connected in series with the main circuit. These coils M are wound with a few turns only of thick wire on a non-magnetic core, so that practically no *inductive drop* of pressure, due to back E.M.F. of self-induction caused by the main alternating current flowing through M, is experienced at full load. The drop in pressure due to the resistance of the series coils is about 0·25 volt in small meters, and less in those for larger currents, while permanent overloads of 50 per cent or temporary ones of 100 per cent are permissible.

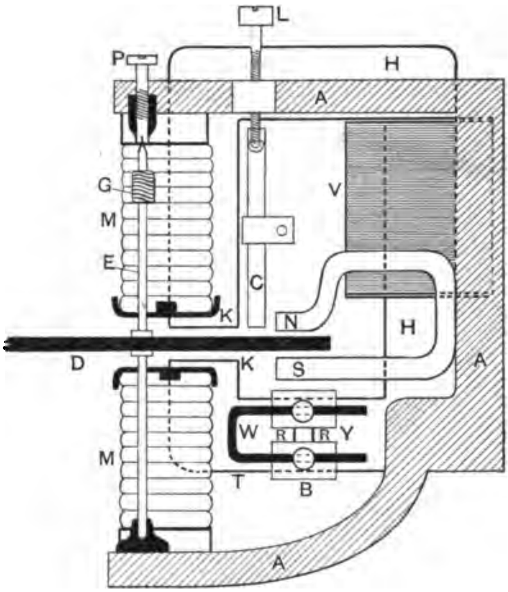


FIG. 135.—Brush Gutmann Meter (Side Elevation).

The coils M are situated so that the magnetic field projected perpendicularly through the disc D, moving in the air-gap between them, exerts a maximum effect in causing its rotation, while the strength of this field

FIG. 136.—Moving System of Brush Gutmann Meter.

is exactly proportional to the current flowing in the coils M. The main aluminium bracket A also supports a well-laminated magnetic

circuit HH, seen plainly in Figs. 137 and 139, and consisting of a number of stampings out of thin sheet charcoal-iron clamped side by side. It is energised by a coil V wound, according to the voltage of the circuit, with a large number of turns of fine copper wire, in order to have as much self-induction as possible. It is connected as a shunt across the circuit or mains which are distributing the power, and the loss in it varies from 0·5 to 3 watts, depending on the voltage and periodicity of the circuit. The laminated iron circuit H contains two

FIG. 137.—Magnetic Circuit of B.G. Meter.

air-gaps, one between K, K, in which the disc D rotates (seen in Figs. 137 and 139), and a much narrower gap between R, R, seen only in Fig. 137. This last-named gap is covered by a heavy copper band B (Figs. 135 and 137), the ends of which do not quite meet, as shown at Y, thus breaking the continuity of the band. This for clearness is shown in Fig. 135 at the side, but is actually on the underside of H.

Each end of B carries a brass connecting block with a hole in it, and a loop of iron or copper wire W is passed through these holes and clamped by set screws (just seen in Figs. 137 and 139), thus completing the electrical circuit through B. When, therefore, the magnetic circuit H is energised so that the magnetic field alternates in

direction between R, R, a secondary E.M.F. and current (p. 183) will be induced in the closed electrical circuit formed by B and W. This current is adjusted to such a strength by clamping W in a suitable position, thereby adjusting the resistance, that it reacts upon the shunt field between R, R just enough to cause it to be in quadrature with the impressed E.M.F. of the mains at the

FIG. 188.—General Side View of B.G. Meter.

terminals of V. Thus the modified magnetic field between K, K induces secondary currents in the disc D, which, when acted upon by the field between M, M, causes the disc to rotate at a speed proportional to the true power given to the circuit with a suitable control or brake. The loop W is really the adjustment for the rate of reversal of the alternating current, and is long enough to adjust for any rate between 60 and 133 complete cycles per second. A screw L, when raised or lowered, actuates the adjustment C for maintaining at light loads the proportion between speed and power measured, which would otherwise be thrown out by the friction at the moving pivots.

Now in order that the speed of the disc D may be directly proportional to the driving torque, *i.e.* to the true power in watts given to the circuit, some retarding force on D must be introduced which shall increase in direct proportion to the speed. Without such a brake, and with only the small amount of friction at the pivots, the speed of

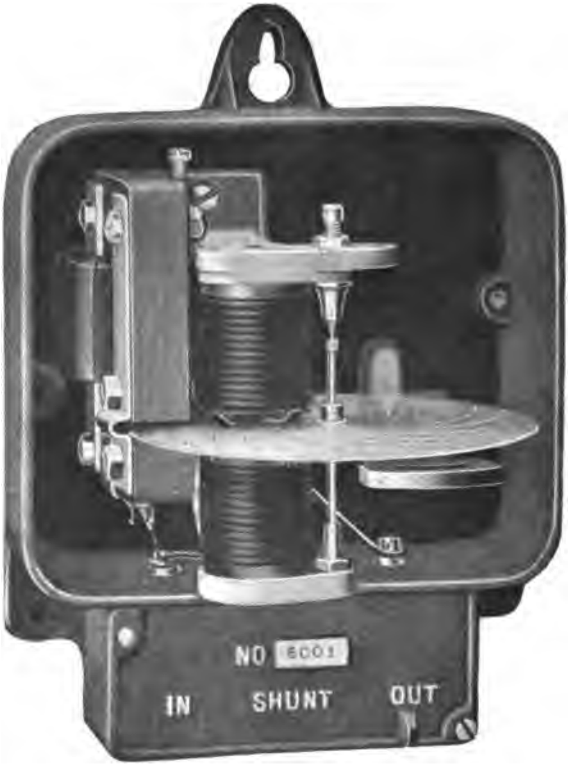


Fig. 139.—General Front View of B.G. Meter.

D would increase almost indefinitely, even though the driving torque remained constant. The brake consists of the combination of the disc D with a powerful permanent magnet which is carefully treated and 'aged,' so as to remain as constant in strength with time as possible. This magnet is shown in Figs. 135 and 138, and the disc D rotates between its two poles N S as seen. Now as the disc rotates, by the principle mentioned on page 193, an E.M.F. and eddy or Foucault currents will be induced in it, which, acting on the constant resistance of the disc, will produce a retardation (*vide* p. 249) proportional to the speed. The moving system will consequently attain a constant speed when the driving and resisting forces balance, and then the watts will

be proportional to speed. The number of revolutions of D is recorded by a delicate train of tooth-wheels driven by the worm G, and the dials of the train can therefore be graduated in B.O.T. units, watt-hours, or kilowatt-hours.

The readings of the meter are given as being true within 2 per cent from starting load (which is very small, and varies with the capacity of the meter) to 50 per cent overload for meters up to 50 amperes, and in larger sizes within 3 per cent from starting to 25 per cent overload, while changes of temperature between 40° F. and 120° F. have no appreciable effect on the accuracy. Meters for currents exceeding 100 amperes are worked in conjunction with a current or series transformer, which reduces the current in the series coils of the meter itself to 5 amperes. On the other hand, a potential transformer is used with meters for pressures exceeding 250 volts. Figs. 140 and 141 show respectively the arrangement of connections to 2-wire circuits, when *series* and *potential* transformers are employed. The arrangement of connections for measuring the power given to a 3-wire single-phase circuit for currents over 50 amperes, using a series transformer, is shown in Fig. 142.

FIG. 140.—Connection through Series Transformer.

Measurement of Insulation Resistance. — This has been accomplished in the past almost entirely with the aid of the so-called 'ohmmeter,' or by a portable and compact collection of apparatus usually termed an 'insulation testing set.' Leaving out of consideration for the present the source of pressure, some kind of which is necessary in every case, the ohmmeter is an instrument which, by the deflection of its pointer on the scale, directly indicates the insulation or other resistance connected to its terminals. Probably the most widely used and best known form is the Evershed ohmmeter, a description of which will be found in nearly all

electrical engineering text-books. Of the other means for measuring insulation resistance there are many different makes, differing somewhat in form and arrangement, but all working on the same principle, namely, that termed the *direct deflection method.* Probably the best known is that commonly called the *Silvertown portable testing set*; and when a tolerably high degree of accuracy is required, such 'sets' may preferably be used, though more care and experience is required

FIG. 141.—Connection through Potential Transformer to 2-Wire Mains.

in their manipulation owing to them not being direct-reading. As both the instruments above mentioned, together with the method of using them, are fully described in *Electrical Engineering Testing* by the author, it is not proposed to give a repetition here.

We shall therefore confine ourselves to the description of a new departure in testing sets, known as the *Everett-Edgcumbe direct-reading resistance and insulation indicator.* It is now generally acknowledged that the Wheatstone-bridge method of measuring resistance, p. 91, when properly applied, is one of the most accurate for the purpose. Messrs. Everett, Edgcumbe, and Co., of London, have designed the present indicator, which not only works on the Wheatstone-bridge principle, but is direct-reading in ohms or megohms, and is both

compact and portable. A general view of the indicator set, complete, with generator (on the right), is shown in Fig. 143, while a diagrammatic sketch of the electrical connections, and also an internal view of the indicator itself, is given in Figs. 144 and 145 respectively. The indicator seen to the left of Fig. 144 comprises a specially arranged high-resistance slide-wire W corresponding to the stretched

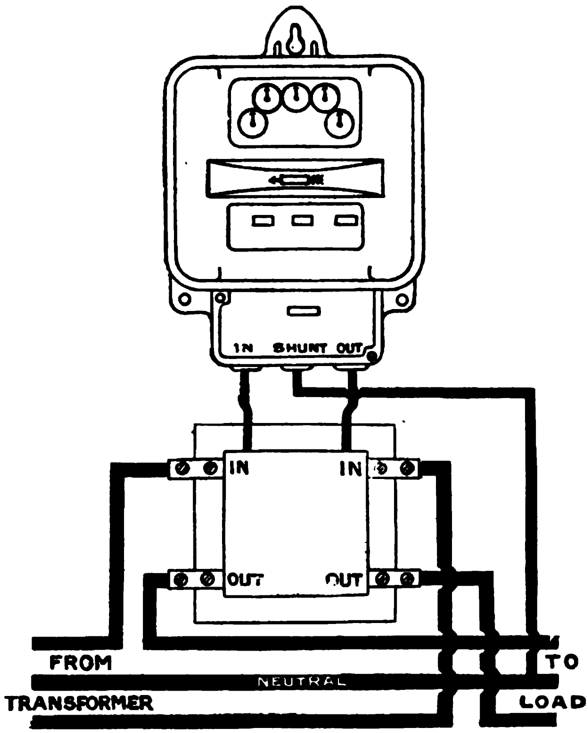


FIG. 142.—Connection to 3-Wire Mains.

wire of a 'metre bridge' (p. 92). In order that this slide-wire W may have a high resistance, say 10,000 ohms, it is formed of silk-covered high-resistance wire wound closely in one layer round a stiff rectangular card about 12″ × 5″, which is afterwards bent round a rigid drum about 4″ diameter and 5″ long. The outside surface of the drum is thus covered with wire, the turns being parallel to its axis, as in the ordinary 'Wirt rheostats.'

In binding the wire-wound card on, a narrow strip is left uncovered, and the insulation being removed from the wires at this position, electrical contact can be made with any turn right round the circumference of the drum. A contact at the end of an arm A moves

round this bared strip of the turns through a circumferential distance of about 12″, thus making contact with any one as at D, and hence with a very large number of equally spaced points throughout the 10,000 ohms of slide-wire between G and E. This contact is fixed

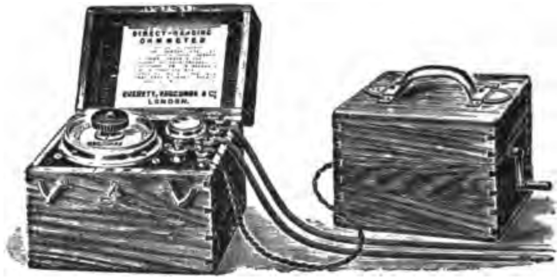


FIG. 143.—General View of Everett-Edgcumbe Indicator Set.

to a central axle carrying a milled head V at the top, by which it can be turned. It is also provided with a pointer moving over a scale, so graduated as to read direct in ohms or megohms as desired.

In order to reduce the standard known resistances r of the bridge to a convenient value, a considerable idle resistance R, wound on a bobbin, is inserted in series with the slide-wire GWX, so that this latter only represents a small portion of the two variable arms DWX and DGRE of the bridge. The standard resistances r are connected

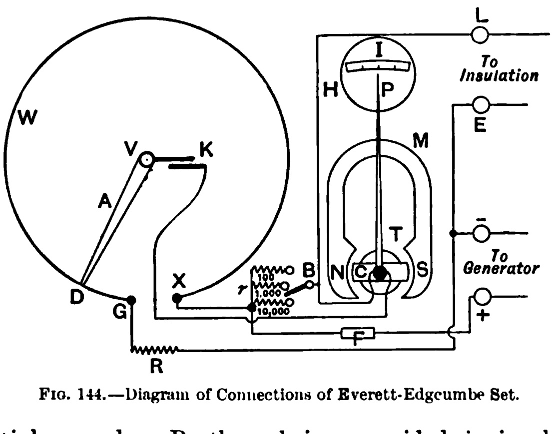


FIG. 144.—Diagram of Connections of Everett-Edgcumbe Set.

to a multiple-way key B, three being provided in insulation sets, having a range of observation from 10,000 ohms to 50 megohms, and five in resistance sets having a range from $\frac{1}{10}$ ohm to 11,000 ohms. For an instrument reading up to 50 megohms, r would be made = 10,000 ohms, while R would be 100,000 ohms. For the measurement of smaller resistances from $\frac{1}{10}$ to 11,000 ohms, the scale is opened

out by inserting an idle resistance at each end X and G of the slide-wire W. The galvanometer, which is also contained in the same case, is an important feature of this set, in that there are no pivots, and no levelling is needed other than placing the case on a floor or table. A D'Arsonval (moving-coil) galvanometer (*vide* p. 211) is used, and consists of a small round coil C capable of turning in the circular air-gap between the pole-pieces N, S of the permanent magnet M and the central soft-iron armature. The coil C carries a pointer P, the motion of which on an index scale I can be seen through a small glass cover-hole H in the top. The coil and pointer are suspended

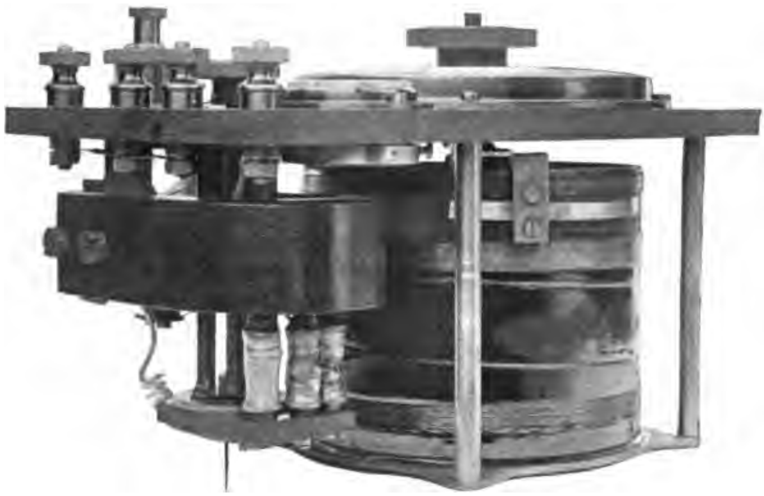


FIG. 145.—Internal View of Everett-Edgcumbe Indicator.

from a brass milled nut T by a spiral suspension, which acts as a spring and so prevents damage to the coil by rough setting down. The pointer can be adjusted to zero by turning T. The galvanometer key K is in the centre of the ebonite milled head V, and can be pressed by the hand which actuates V.

To take a measurement of resistance, the resistance to be determined is connected to terminals L and E; or, if this is the insulation resistance of the wiring of a building, the copper core of one of the wires is joined to L, and E is connected to the nearest gas or water pipe so as to obtain a good 'earth.' A suitable source of E.M.F., at least as great as what the installation will eventually work at, is joined to terminals + and −, and r is set to a suitable standard resistance. A position is then found for the ebonite milled head V, so that on pressing the key K no motion of the galvanometer

pointer P is observed. The value of the resistance is that shown on the dial opposite the pointer of the indicator. The scale of the indicator is shown in Fig. 146, from which the extreme openness of it can be seen, and also that the maximum reading is eleven times the minimum. The outer scale, which is 12″ long,

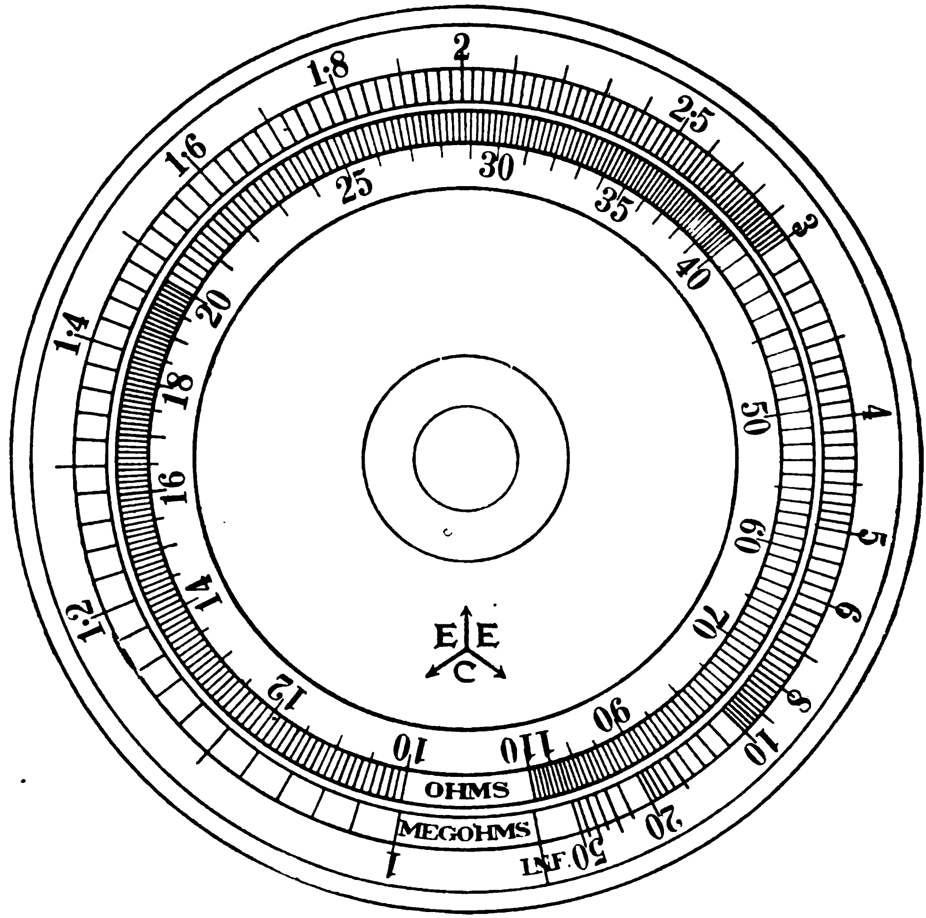


FIG. 146.—Scale of Everett-Edgcumbe Indicator.

ranges from 1 to 50 megohms, while the two remaining ranges of the instrument are 10,000 to 500,000 and $\frac{1}{10}$ to 5 megohms. For insulation measurements a magneto-generator is supplied, giving 100, 200, or 500 volts as desired. Particular care has been taken with the design of the brushes (which are plumbago rods) and the commutator, which is of a special ring form to minimise sparking,

friction, and wear. The spindle runs in ball bearings, and is consequently very easy to turn.

The indicator, being quite unaffected by external magnetic fields, can be used close to a dynamo or its own generator without the readings being affected. Furthermore, it is quite immaterial as to which way the generator is turned. The inner scale of Fig. 146 is for use when measuring resistances from $\frac{1}{10}$ ohm to 11,000 ohms in the case of the lower resistance indicators, and does for the five ranges. If this scale is 12″ long, the total range of $\frac{1}{10}$ to 11,000 is read off on a scale having the equivalent length of 5 feet. From a reference to page 91 *et seq.*, it will be understood that the indications are unaffected by the voltage, though the test becomes more sensitive as the voltage is increased. A pressure of 200 volts is found quite sufficient for ordinary insulation work; and when great accuracy is desired, as with street mains, where the capacity is usually large, a battery of primary or secondary cells (preferably the latter) is better than the usual generator. For ordinary resistance testing, say from $\frac{1}{10}$ to 11,000 ohms, two or three Léclanché cells are ample.

Maximum Demand Indicators.—These are instruments of modern origin which have been introduced in connection with the supply of electrical energy for public purposes with the object of enabling both large and small consumers to be charged on an equitable basis. The manner in which the demand indicator is used arises from what is now commonly known as the *maximum demand* system, the principle of which is to charge every customer in proportion to what it costs to supply him, plus a reasonable profit. Experience has shown that some customers are very much more profitable than others to an electricity supply undertaking, no matter what price may be charged per unit. Thus, the consumer who uses his lamps for a considerable number of hours daily throughout the 24, is usually a much more profitable customer to the supply company than one who takes exactly the same amount of electrical energy in a much shorter period of the 24 hours. A small customer paying a small bill may in this way be more profitable than a large customer paying a large bill. The late Dr. John Hopkinson was one of the first to point this out, the reason being that, while the meters of both consumers might read the same in any given period, the cost of supplying a given amount of electrical energy for a given time, say 10 hours, is much less than ten times the cost of supplying that same amount for 1 hour.

The reader will at once realise that if all the customers had all their lamps '*on*' at the same time for any period of the day, the

supply station would have to be much larger, and therefore much more capital would have to be expended on it, than if the same amount of electrical energy was supplied over a much longer period. Hence the proportion of capital expended for which each customer is responsible does not depend on the total amount consumed, but on the maximum amount at any one time, *i.e.* on his *maximum demand.* For all customers to be treated equally fairly, the one who has the greatest maximum demand should pay more per unit than one whose maximum demand is less. In practice, therefore, the method adopted is as follows :—The *maximum demand* of the customer, or the greatest amount of electrical energy which he takes at one time, is measured by what is called a *maximum demand indicator* or *rebate indicator,* as it is variously termed, which is installed in addition to the ordinary meter. He is then charged the full rate per unit for a certain number of units out of the total number consumed during any given period, the remainder being subject to a very large discount or rebate. The first charge covers the *standing* expenses of the station ; the second one, after rebatement, covers the *running* expenses, which are a small fraction of the whole. Besides having to be a type of registering ammeter, the demand indicator must, to a sufficient extent, be sluggish in its action, *i.e.* it should take no notice of a sudden momentary rise of current lasting a minute or so, and due perhaps to a batch of lamps being turned on just before, instead of just after, another batch is turned off.

Since an appreciable amount of energy is absorbed in the instrument on account of the addition of a registering device in some cases, the *electro-magnetic* (moving soft-iron core) and *thermal* principles lend themselves to the construction of demand indicators.

We may now describe one form of instrument made by the Schattner Electricity Meter Company which has been approved by the Board of Trade, namely, the Atkinson-Schattner Maximum Demand Indicator. The construction of this is very simple, and will be understood from a reference to Figs. 147 and 149. It consists of a rather special form of ammeter of the electro-magnetic moving soft-iron core type, reading direct in amperes and to which is added a registering device that in no way affects the action of the instrument other than very slightly increasing the friction at the pivots, due to a slight increase of weight on them. The ammeter portion comprises a curved soft-iron plunger or core HI, well laminated by being built up of a number of curved, thin soft-iron strips riveted together as indicated, the core gradually increasing in thickness towards the end H. This tends to make the pull as uniform as

possible throughout the range. This is indicated in the curve, Fig. 148, taken from a 10-ampere indicator of an early construction. This core is carried at the end of an aluminium arm F pivoted on a horizontal spindle running in jewelled centres which are carried by the bracket arm D. This arm F is expanded above the centre into an aluminium sector frame. The core HI is capable of being sucked into a curved solenoid C, wound with insulated copper wire sufficiently

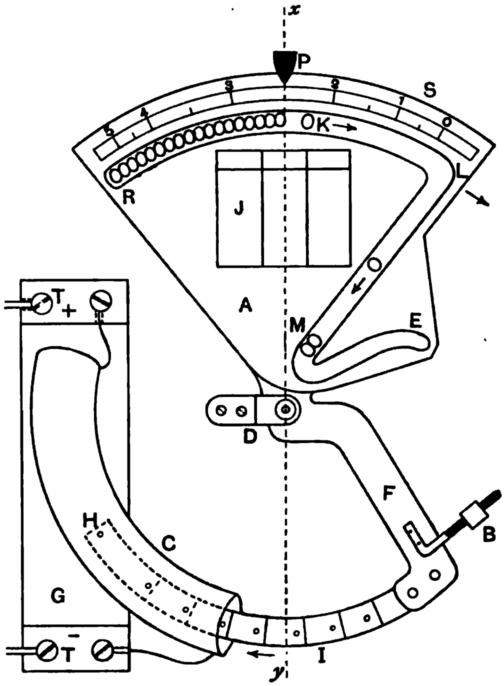


Fig. 147.—Principle of the Atkinson-Schattner Maximum Demand Indicator.

thick to carry the main current, and supported on an insulating block G, which also carries the brass terminal blocks T.

The registering device consists of a light but fairly rigid sector-shaped card A engraved with the scale S of amperes at the top, and carrying a curved glass tube RL terminating in the straight limb LM and leg ME. A pointer P is fixed to the containing-case of the indicator, and shows the current corresponding to the deflection of the scale and moving system against the controlling force of gravity. A balance-weight B, which can be screwed out or in, serves as an adjustment for the position of the moving system at the outset. The registering tube RLM contains about twenty steel balls, each about $\frac{3}{16}''$ in diameter, and is filled with a viscous liquid, such as glycerine or oil, through

which the balls can move slowly. Since the highest point of the tube RL lies in the vertical line xy, any ball (*e.g.* K) to the right-hand side of xy, as HI is sucked into C by increase of current, begins to roll down toward M. Consequently the maximum current which has passed, since the instrument was last set, is indicated by the number of balls which have left the bend RL and collected in the limb LM. The minimum time of action of the tube is about two minutes, which is sufficient to prevent any of the balls rolling down due to a short-

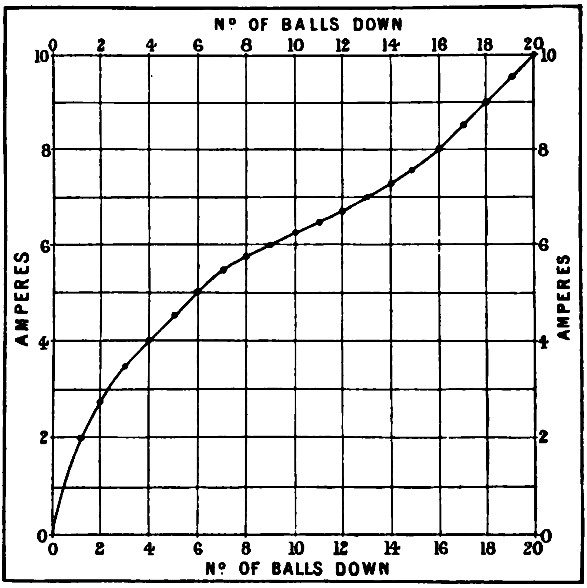


FIG. 148.—Curve for Atkinson-Schattner Maximum Demand Indicator.

circuit, vibration, or momentary increase in the amount of current taken.

The actuating principle employed, however, prevents a uniformly graduated scale being obtained, and, furthermore, every ball does not represent either a definite current or the same increment of current. A calibration table J therefore occupies the vacant space on A, having in the first column, *number of balls down*; second column, corresponding current in amperes; third column, number of units to be consumed before the lower rate of charging comes into force. This is shown in Fig. 149, which is taken from a photograph of one of the latest forms of instrument, having a capacity for 5 amperes. In order to avoid wasting the meter-reader's time in resetting the indicator by waiting for the balls to slowly return from ML to the curved

tube RL, a duplicate scale card and tube is hung upside down on the inside of the door. This resets itself at leisure, and is always ready to replace the one in use at any time. Each instrument is independently calibrated and tested for either direct or alternating currents, and is made for any current from 2½ to 1000 amperes. The voltage of the circuit of course merely affects the amount of insulation to be provided for in the electrical portions T and C of the indicator.

The registering tube has to be most carefully made, especially the part RL, which is separately shaped very gradually inside a muffle

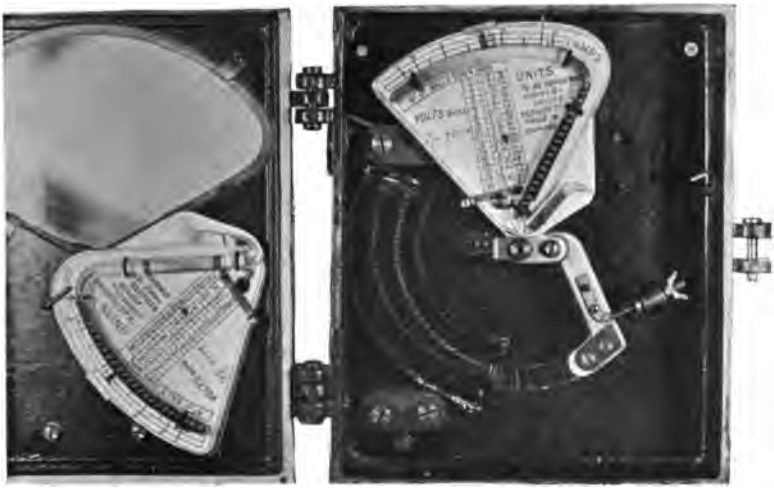


FIG. 149.—Interior of Demand Indicator.

furnace to insure perfect symmetry and absence of straight portions. It is then joined to the rest of the tube LME, and after the insertion of twenty steel balls, is exhausted of air by an air-pump. It is next opened at the end E under oil or glycerine, etc., which is thus forced into the tube. A little bubble of air is left at end E to avoid the fracture of the tube from the expansion of the liquid due to rise of temperature. Owing to the cost of supply and other conditions varying in different towns, the rebate scale to be entered at J varies, but any scale can be entered without in any way affecting the instrument. Usually a rebate is allowed after a consumption equal to that of about one hour's use per day during any quarter of the maximum current registered. This is about 91· hours per quarter, but a round number of 100 is adopted usually. If now the price per unit be 6d., then a system of rebate which would commend itself would be 6d. for the first 100 hours' consumption at the maximum

rate of demand, 4d. for the next 100 hours, and 2d. afterwards, and this would merely necessitate an additional column in the table J. Space will not permit of further discussion on the uses of the demand indicator; suffice it to say that the introduction of the maximum demand system of charging for electrical energy is greatly helping to stimulate the sale and use of this most important agent.

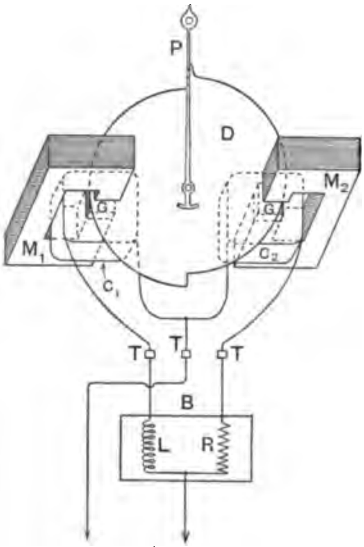


FIG. 150.—Principle of Westinghouse Frequency Indicator.

Frequency Indicators.—These are instruments intended for use with alternating currents only; in fact, they will not work with continuous currents, even if there is any object in using them with such. There are many instances in which it is highly desirable, and in others necessary, to know the rate at which an alternating current reverses, *i.e.* the number of complete cycles per second, which is called the *frequency* or *periodicity* of the alternating current.

There is more than one form of instrument for indicating frequencies, but we shall confine ourselves here to that designed and made by the British Westinghouse Electric and Manufacturing Company, of London, etc. A diagrammatic sketch of the working parts of this Westinghouse frequency meter is shown in Fig. 150, while its connections to the circuit, together with a general view of the instrument, are given in Figs. 151 and 152 respectively. It consists of two well-laminated magnetic circuits M_1, M_2, built up of rectangular stampings out of the finest Swedish soft annealed charcoal-iron sheet. A narrow gap is formed in one of the sides of each stamping, so that when they are lightly insulated on one face and assembled side by side to the required width there is a narrow air-gap (G) or break in each of the laminated magnetic iron circuits M_1 and M_2. The longer of the two polar limbs of both M_1 and M_2 is wound with a coil (C_1 or C_2) of fine insulated copper wire, the ends of which are connected to the terminals T of the instrument as shown (Fig. 150).

The moving system consists of a thin aluminium disc D of rather peculiar shape, carried, together with a light pointer P, on a horizontal

spindle which runs in jewelled centres. This moving system is very carefully balanced so as to rest in any position, and no form of control whatever is employed with it. It is capable of moving freely through the narrow air-gaps G of M_1, M_2, the poles of which just embrace the outermost surface of the disc. A series resistance-box B is supplied with the instrument, and contains an *inductive* resistance L and a *non-inductive* resistance R connected as shown. It will now be seen that between the two wires W which connect the whole arrangement to the mains, the frequency of the current in which

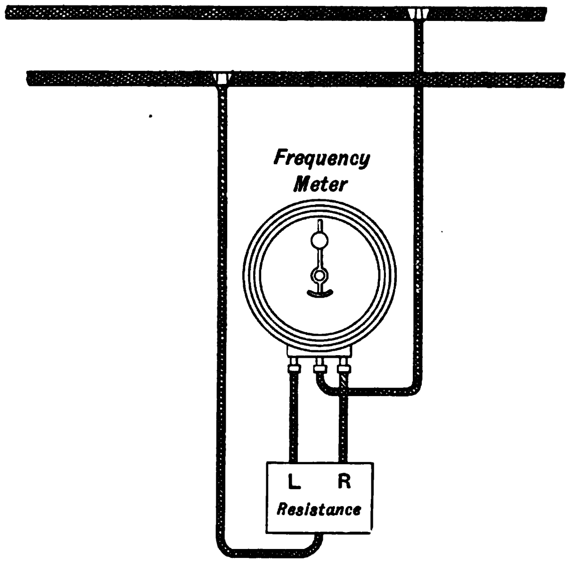


FIG. 151.—Connections of Westinghouse Frequency Indicator to Circuit.

is desired, there are two circuits in parallel, namely, L and coil C_1 in parallel with R and coil C_2. But C_1 and C_2 being similar coils and L inductive, an increase in frequency will cause a diminution of the current strength in the branch LC_1, and therefore a diminution in the magnetic field in the air-gap of M_1. Moreover, the current in branch LC_1 will lag in phase more than that in RC_2 behind the E.M.F. at the ends of the parallel circuit. Consequently the electro-magnets M_1, M_2 tend, by reason of the currents which they induce in D (p. 193) and the phase differences of these currents, to cause the disc D to rotate in opposite directions. The disc D and its pointer P therefore come to rest when these opposing forces just balance one another.

But any change of frequency will, by alteration of the currents

in the branches, as we have seen, alter the relative values of the torques due to M_1, M_2, so that the disc D will move to some new position where the forces again balance. Hence the scale divisions can be made to represent frequency or periods per second, and, as will be seen from Fig. 152, are fairly open. The connections between indicator and resistance-box must be made exactly as shown in Fig. 151; while for circuits having a higher voltage than 100 to 125 a pressure-reducing transformer is used which reduces that of the mains to the value needed for the indicator. The makers calibrate all their standard frequency indicators on mains supplied from a generator having a slotted armature; when, therefore, the instrument is used on a circuit having another *wave-form*, the indications will not be correct, and a re-calibration is necessary. The foregoing description of the principle of action of this frequency indicator will no doubt be more easily understood after the reader has studied the theory of alternating currents.

FIG. 152.—General View of Westinghouse Frequency Indicator.

Power-Factor Indicators—Phasemeters.—These are special instruments for use with alternating currents only, and in dealing with them at this stage it is assumed that the reader has made himself familiar with the principles and terms relating to alternating-current work. As he will have seen, the fluctuation of pressure and current is not only alternating in direction, but each takes the form of a wave-curve by means of which the instantaneous values of pressure and current can be obtained at any moment of the cycle or period of variation. It is only when the circuit through which the current flows possesses neither self-induction nor capacity, or, in other words, is non-inductive, that the pressure and current waves coincide in their points of minima and times of maxima. Under these circumstances the current is said to be '*in phase*' with the pressure, and the true or effective power expended in the circuit will be the amperes × volts, while the '*power factor*' is said to be 1. If, however, the circuit is inductive, the current wave is either displaced behind, or in front of, the E.M.F. wave (depending on whether the circuit possesses self-induction or capacity in preponderance) by a certain amount known

as the phase difference and given by the angular distance along the base line between their succeeding points of minima. The product amperes × volts is now termed the *apparent power*, while the *true power* can only be indicated by a wattmeter. The ratio $\frac{\text{true power}}{\text{apparent power}}$ = cosine a, or the power factor which under such conditions is always less than 1, while a is the angle of phase difference.

Self-induction tends to cause the current to *lag* behind, and capacity tends to make it *lead* in front of, the pressure. The current, as indicated on an ammeter with these conditions, is the resultant of the *load current* which is in phase with the E.M.F. and does useful work in

FIG. 153.—Interior of Everett-Edgcumbe Power-Factor Indicator.

the circuit, and of the *idle* or *wattless current* which is dead out of phase with the E.M.F. and does no useful work in the circuit. From the foregoing brief explanation it will be obvious that an instrument capable of indicating either power factor or phase difference will give an indirect measure of the other quantity. There are several forms of power-factor indicators which belong to one or other of two types, namely—instruments indicating merely the wattless component of the whole current which is flowing in the circuit; and instruments indicating the actual power factor or angle of phase difference between amperes and volts.

We will now consider one of the last-named type, devised and made by Messrs. Everett, Edgcumbe, and Co., of London. Fig. 153 is a view of the interior, showing one of the current coils removed in

order to enable the moving-coil system to be seen. In the case of a balanced three-phase circuit, the instrument consists of a fixed-current coil, in two halves as shown, which is inserted in one of the mains. The moving system comprises three fine-wire or pressure coils fixed, with their magnetic axes (*vide* p. 131) at an angle of 120° to one another, to a spindle which also carries the pointer and is pivoted in jewelled bearings. Electrical connection is made to the three pressure terminals of the indicator from one end of each of the three moving coils through the medium of three fine phosphor bronze hair-springs. The remaining three ends are joined together and form a *neutral point*. Thus the moving system somewhat resembles the armature of a Thomson-Houston arc-light dynamo, or that of the meter described on page 248.

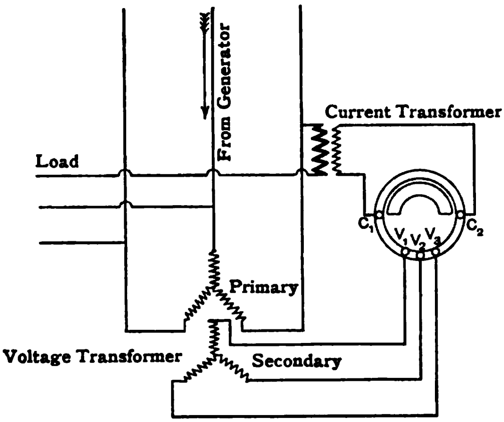


FIG. 154.—Diagram of Connection for Balanced Load.

A rotating magnetic field is thus produced, and the moving system will turn so as to set itself in such a position that, at the moment when the current in the fixed coil reaches its maximum value, the magnetic field due to the moving system lies along its diameter. The field will rotate in one direction or the opposite, depending on whether the current *leads* in front of, or *lags* behind, the E.M.F., *i.e.* on whether capacity or self-induction predominates in the circuit. Thus the pointer by its direction of rotation will indicate this, and also the magnitude by the angular deflection.

In the case of an unbalanced system, three fixed coils are employed also, set at an angle of 120° to each other; one being supplied, either directly or through series transformers, from each main. A similarly constructed moving system to that described above moves inside these three current coils and takes up a position corresponding to the *average* power factor of the whole system. By the insertion of plugs so arranged as to short-circuit any two of the current coils, the average power factor of the phase containing the remaining coil can be indicated. For high-tension systems, transformers are employed both in connection with the volt or moving coils and also with the

current or fixed coils. The arrangements for connecting a three-phase power-factor indicator in balanced and unbalanced circuits are shown in Figs. 154 and 155. The moving coils are sometimes

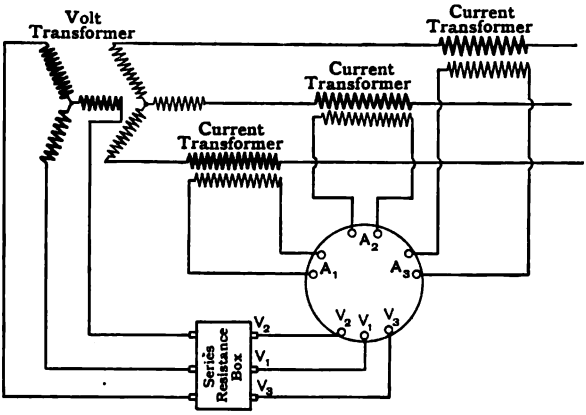


FIG. 155.—Diagram of Connection for Unbalanced Load.

connected to the three mains through a series-coil resistance-box, as is shown in Fig. 155. Fig. 156 shows the general appearance of this make of instrument, which has the advantage that its indications are independent, not only of the voltage of the supply mains, but also of the *frequency* and *wave-form*. This is a unique feature, as the usual construction of instruments of this kind, in which a phase difference

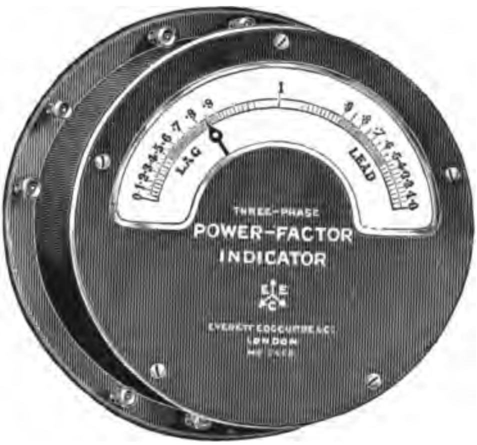


FIG. 156.—General View of Power-Factor Indicator.

is produced by means of an inductive or a non-inductive resistance, is, of course, only accurate at one particular frequency and wave-form.

Electrical Thermometers—Pyrometers.—Increasing attention is being given by manufacturers at the present day to the accurate measurement of high temperatures in commercial processes. The importance of such measurements is becoming more and more apparent, especially in engineering and kindred trades, and manufacturers are beginning to realise this. The inapplicability of the ordinary mercurial thermometer to the measurement of even mediumly high temperatures is well known. This has led to the introduction of what may be termed *metallic thermometers*, the principle of which is to obtain a measure of the temperature by the corresponding thermal expansion or contraction of one or more solid metals arranged in some convenient form. Although such thermometers can generally be used for measuring higher temperatures than a mercurial thermometer could bear, they cannot be used for measuring the temperature of many furnaces, owing to the certainty of fusing the metals employed in their construction. Thermometers for measuring very high temperatures have received the name of *pyrometers.*

The importance of such instruments was evidently realised some years ago, for Brongniart, of the porcelain factory at Sèvres, and Wedgwood, the famous potter, both attempted the construction of pyrometers: the former by magnifying the expansion of a long iron bar placed in the furnace, the latter by constructing a gauge for measuring the expansion and contraction of a piece of baked clay placed in the furnace. None of these attempts gave consistent results, and the *air thermometer* had to be fallen back on for very high temperatures. Recent years have, however, witnessed the introduction of the so-called *electrical pyrometer*, which can be used to measure low, medium, or high temperatures up to 1600° C. and over without any trouble, and, as a general rule, with an accuracy to something like 0·5 % with care. It is almost superfluous to point out the great future before an instrument of this kind with such a range and degree of accuracy, and in view of the fact that if necessary the indicating portion may be placed as far away from the thermometer portion as desired.

A few instances of its use may, however, be instructive; for example: In the maintenance of constant temperature in the various rooms of *cold-storage* and other warehouses (range − 10° to 10° C., *i.e.* 14° to 50° F.). In the wards of hospitals which are heated by hot water, steam, or the 'plenum' air system (range, 0° to 20° C., *i.e.* 32° to 68° F.). In breweries, for controlling the temperature of the mash-tuns or keeves, recording the temperature of the *wort* and the cold hop stores. In chemical works, for measuring the temperature of 'stills' and 'vats,' etc. In other industries, particu-

larly those connected with iron, steel, glass, pottery, tile, brick, gas, galvanising, and steam-producing appliances, the question of temperature is of supreme importance. In some of these, temperatures of 2700° F. and over are reached, and the variation of a few degrees, notably in connection with annealing furnaces and the metallurgy of iron and steel, at certain critical stages, may be fatal to the success of the process and cause considerable loss. The accurate measurement of temperature in steam boilers, superheaters, flues, destructors, etc., cannot help but lead to increased efficiency through localisation of waste. Having now given the reader an idea of the importance of electric thermometers or pyrometers in all kinds of commercial work, we will next turn to their construction.

There are two distinct types, differing chiefly in the principle on which the measurement is made, namely: (1) *thermo-electric pyrometers*, which depend for their action on the current generated by heating a thermo-couple up to the temperature that it is desired to measure (*vide* p. 385); (2) *electrical-resistance thermometers*, or those indicating temperature by means of the corresponding alteration in the electrical resistance of a coil of wire (*vide* p. 72). The former type, although not so accurate as the latter, is much more suitable for measuring high temperatures up to 1600° C. (2900° F.), such as those met with in blast and puddling furnaces, smelting, pottery and glass works, and is less costly. For this reason they are preferable in cases where there is a great risk of damaging a thermometer, but on the other hand they require more frequent standardising than the 'resistance' type. The thermo-electric pyrometer comprises a thermo-electric couple consisting of a wire made of a platinum alloy containing rhodium, nickel, or iridium and a pure platinum wire, melted together at one end. This junction, and from 1 to 6 feet (depending on requirements) of each wire, either side of the junction, is encased in a thermometer-tube of special construction, and the two free ends brought out to two terminals at one end in such a way that the measurements are unaffected by any ordinary rise of temperature at this end. The other end of the tube, at which the *junction* is situated, is exposed, and hence also the junction itself, to the temperature to be measured. The special tube differs in construction according to the maker, but in all cases the object of it is to insulate the wires from each other and protect them from mechanical injury and the chemical action of any flues or gases.

The form of construction adopted by Messrs. Hartmann and Braun, of Frankfort-on-Main, is shown in Fig. 157, and consists of an outer fire-proof tube composed of several short lengths, each having two small

Fig. 157.—Hartmann and Braun Thermo-electric Pyrometer.

1:3

holes through from end to end, one on either side of a larger central hole. These short lengths are threaded to the desired length over a central metal tube, which, for temperatures up to 1000° C., is made of special steel, and above 1000° C. of platinum, for the length that projects into the furnace. The lengths are under a constant compression obtained by means of a spring and clamping-nut at the terminal end, and the wires pass through the two lines of small holes, which register with one another. The current produced by the E.M.F. set up in the thermo-couple, and which is a measure of the temperature to which it is heated, is in all makes indicated on a sensitive high-resistance moving-coil permanent-magnet voltmeter (*vide* p. 230) having its scale graduated in degrees of temperature. Owing to its high resistance, it can be used some distance away from the pyrometer without the resistance of the connecting wires or the variation of temperature of the voltmeter introducing any error.

Electrical - Resistance Thermometers.—Turning next to this type of instrument, which is not suitable for temperatures exceeding about 700° C. It consists of a fine platinum wire, which may be termed the bulb of the thermometer, wound on an incombustible but insulating frame, usually mica, and placed in a porcelain or metal protecting tube, according to the temperature to be measured. Either copper or platinum 'leading-out wires' connect the fine-wire coil to the terminals. In this type of thermometer the various makes differ chiefly in the means for measuring the resistance of the coil, which increases as the temperature increases, the value of which is therefore a measure of the temperature to be determined.

That introduced and made by Messrs. Siemens Bros. and Company, of London, in their direct-reading pyrometer, is shown diagrammatically in Fig. 158, and depends for its action on the principle of the Wheatstone bridge (*vide* p. 90). It consists of an adjustable resistance YK in the form of a helical coil of wire, which is arranged round the edge of a circular dial mounted on a tripod. The dial is graduated in either Centigrade or Fahrenheit degrees, and carries in

the centre a small moving-coil permanent-magnet galvanometer G (p. 211). A sliding contact, with a pointer, serves to adjust the resistance of the variable arm of the bridge and to indicate on the dial the temperature of the pyrometer coil at the moment of 'balance,' *i.e.* when the galvanometer does not deflect on pressing the knob for the position of the sliding contact found. The keys are combined and fitted to the sliding contact so that the act of pressing the knob of this contact connects the battery, galvanometer, and pyrometer. The two remaining arms, CX and CY, of the bridge may be any two convenient equal resistances. It will now be seen that considerable accuracy can be obtained with an arrangement such as the above, and there is the further advantage that the indicating instrument is compact and direct-reading, while at the moment of balance there is no deflection to be read.

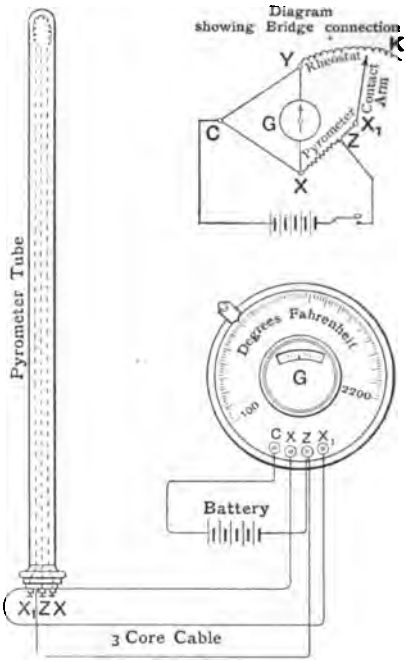


FIG. 158.—Principle of Siemens Pyrometer.

The Cambridge Scientific Instrument Company, who are large manufacturers of both thermo-electric and electrical-resistance thermometers, make some excellent forms. Fig. 159 illustrates a resistance thermometer P, connected by flexible wires to a Whipple patent temperature indicator. The thermometer itself varies slightly in construction, according to the purpose for which it is required. Fig. 160 illustrates the construction suitable for general testing work, including the measurement of the melting-points of metals, etc., and for temperatures up to 1400° C. (2552° F.). The porcelain tube, 12″ (300 mm.) long, is protected by a removable steel sheath, which must be removed for temperatures exceeding 500° C. or 700° C. (1292° F.). In thermometers to be used in high-temperature furnaces the tube is porcelain and the leads platinum throughout. The Whipple patent temperature indicator mentioned above enables the temperature to be read off directly on a scale, either in degrees Centigrade or Fahrenheit. The principle involved in it is that of a Wheat-

stone bridge, the arrangement being represented diagrammatically in Fig. 161. It consists of two ratio or proportional coils x and y, the thermometer coil C in series, with a long bridge-wire W, which is wound on a frame in the form of a helix. A contact D, capable of moving round the helix W, and of making connection with the wire of the helix at any point in its length, is actuated by turning the milled head H (Fig. 159).

The position of the point of contact is indicated by an index-

FIG. 159.—Resistance Thermometer and Whipple Indicator.

pointer on the scale A (Fig. 159), which is graduated in temperature degrees. The compensating lead L is connected as shown, and is one of the two pairs shown in Fig. 159, arranged to be under the same temperature conditions as the remaining pair, which go to the thermometer coil. Since, therefore, any change of resistance of the leads going to the platinum coil is accompanied by an equal change in the compensating leads L, the want of balance on the bridge will be due to the thermometer coil itself. A sensitive galvanometer B, the index-pointer of which can be seen at B (Fig. 159), is connected as shown, as also a two-cell dry battery G and battery key F. Referring

to Fig. 159, the leads going to the thermometer coil itself are connected to terminals T, those to the compensating coil to the other pair of terminals next to T. Then by closing the battery key F and turning the head H until the index at B comes to zero, the temperature of P can be read off directly on the scale A in degrees Centigrade without any corrections whatever. The company have recently installed some resistance thermometers in the Royal Arsenal, Woolwich, the indicators for reading which are in an engine-room three-quarters of a mile away.

Fig. 162 shows one of these thermometer sets in use on a Brayshaw's steel-hardening furnace. In this work Mr. S. N. Brayshaw, of Manchester, who is a specialist in hardening steel, contends that 5° C. makes the difference between good and bad hardening. The platinum thermometer in conjunction with a recorder, such as Callendar's electric recorder, furnish a continuous record over a week or less, an observer being able to read the temperature without disturbing the record. Such a combination is shown, about $\frac{1}{6}$th full size, in Fig. 163 and indicates a Callendar and Griffiths' patent resistance thermometer connected to a Callendar recorder. The necessary two-cell storage battery, capable of running for a week, is shown just below the recorder itself. Fig. 164 shows an annealing furnace record taken by such a combination as that just mentioned. The temperature is above 700° C., and each space on the vertical

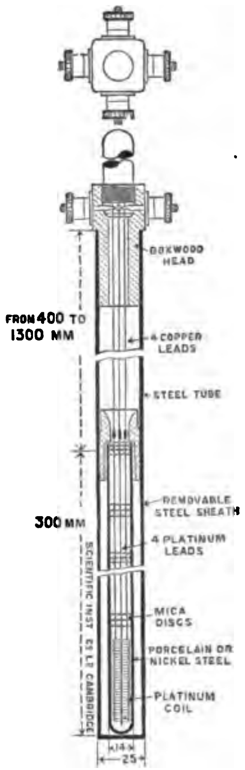


FIG. 160.—Section of Resistance Thermometer.

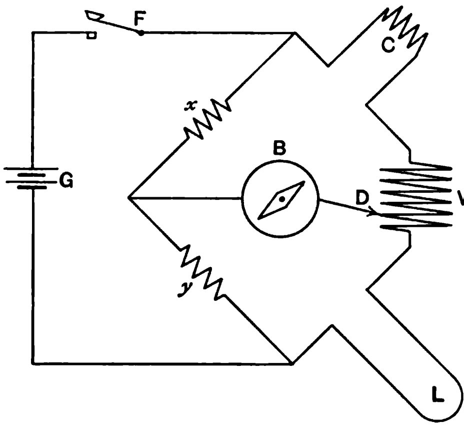


FIG. 161.—Principle of Whipple Patent Temperature Indicator.

scale = 4° C., the horizontal length of the diagram is nine hours. The difference in the firing of the two stokers A and B can be seen very clearly: the times of firing are indicated by the well-marked notches on the curve.

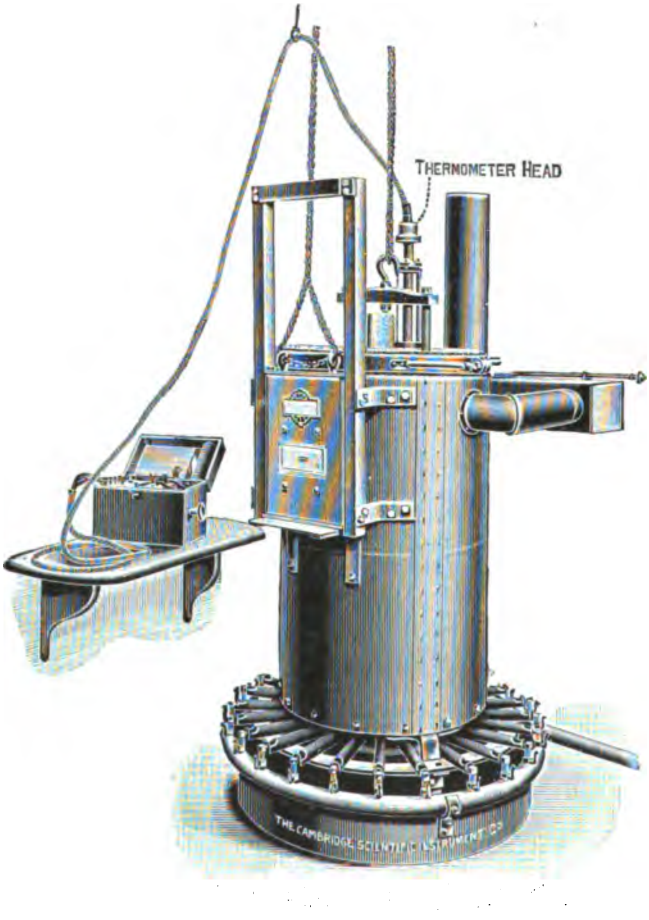


FIG. 162.—Resistance Thermometer in a Steel-Hardening Furnace.

Magnetic Testing Sets—Permeameters.—From a perusal of page 143 *et seq.* the reader will be familiar with two very important characteristics common to all magnetic material, namely, its magnetic *permeability* and *hysteresis*. Of late years several different pieces of apparatus, of somewhat special construction, have been devised for the purpose of measuring more easily the above-named quantities. With merely one or two exceptions, such apparatus, and also the older

methods on which the measurements with them are mostly based,

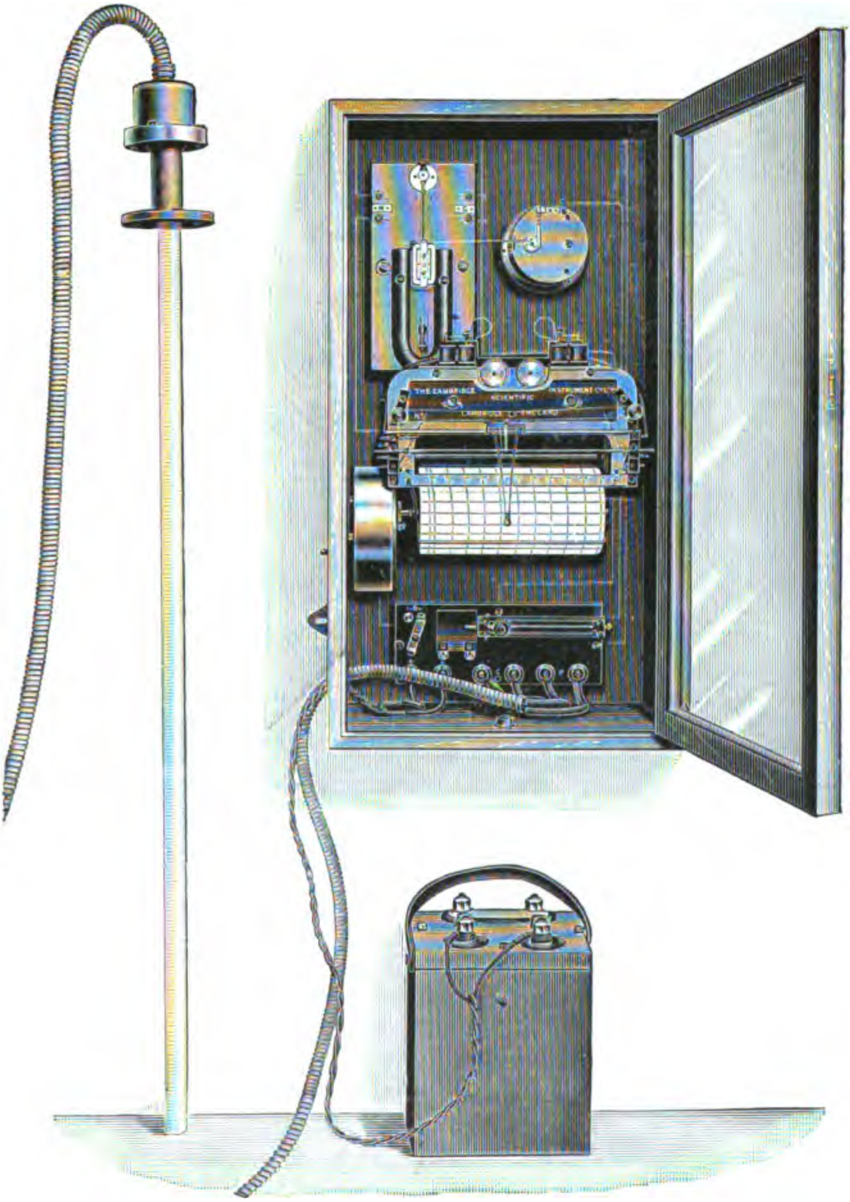


FIG. 163.—Resistance Thermometer connected to Callendar Recorder.

require samples in the form of either continuous rings or long rods, which are sometimes troublesome to obtain. Moreover, it is well

known that two similar castings from the same foundry at the same time may differ considerably in permeability, even when run from the same pot of molten metal, owing perhaps to one being chilled more than the other, or to some other cause.

It will therefore be seen that a specimen ring or rod may not be at all representative of the casting, even when from the same pot, and the test on such is often therefore of little value. With the view of overcoming these difficulties, a magnetic testing set has recently been devised by Dr. C. V. Drysdale, and is now made by Messrs. Nalder Bros. and Company, of London. The object of it is to enable manufacturers who buy iron and steel for magnetic purposes to test the permeability and hysteresis of the castings or forgings themselves when they arrive from the foundry, and thus obtain a trustworthy deter-

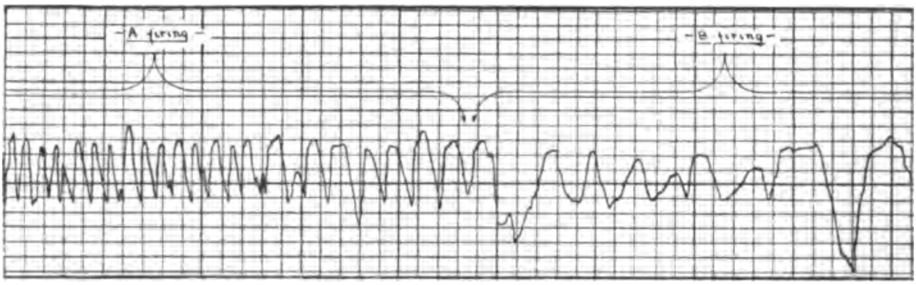


FIG. 164.—Temperature-Time Curve given by Resistance Thermometer.

mination of working values and an accurate estimate of the excitation necessary. The complete testing set, arranged in portable form, is illustrated in Fig. 165, and the diagram of connections in Fig. 166, while enlarged and detail views of some of the parts are shown in Figs. 167 to 171. The principal parts comprise a special form of drill for drilling a certain sized hole in the casting to be tested; a testing-plug, which just fits the hole so drilled; a portable box containing a battery of two large dry cells, which are connected in series with an adjustable resistance consisting of a series of resistance coils, connected with a multiple block-switch to the battery reversing key.

By this means different values of magnetising force, ranging from $H = 5$ to $H = 100$ C.G.S. units, or gausses, can be obtained and read off on an ammeter (H, Fig. 166), the scale being graduated directly in values of H for a given testing-plug. From the above-named reversing key, connection is made to the two terminals marked M, M, to which the flexible leads from the magnetising coil of the plug are joined. A small resistance coil CC is joined in series with the magnetising coil to compensate for the magnetic lines passing through

the air-space surrounding the test specimen. The search coil on the plug is connected to the two terminals marked S, S, whence its discharge passes through the galvanometer reversing key to the ballistic galvanometer (B, Fig. 166), which for a given plug has its scale divided directly in values of B or lines per square cm.

FIG. 165.—Complete Testing Set.

Placing the galvanometer key in its central position, instead of breaking the galvanometer circuit, puts it in series with a resistance which doubles the total resistance of the circuit. The object of this is that when measuring permeability and taking ordinary magnetisation curves, the throws would be otherwise doubled owing to them being obtained by reversing the magnetising current. In measuring cycles of magnetisations the current is simply *made*, *broken*, or *increased*.

Returning to the special drill which is shown in Figs. 167 and 168. It has four cutting edges at the lower end, which cut a cylindrical hole

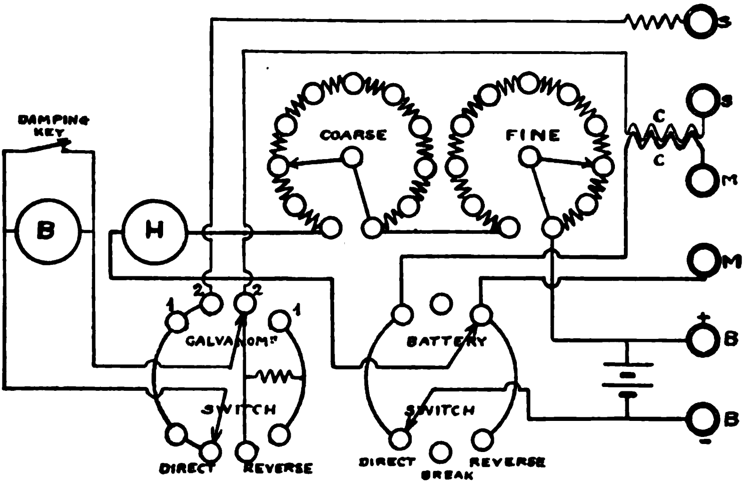


FIG. 166.—Connections of Magnetic Testing Set.

in the specimen. The drill is, however, made hollow, so that a thin rod or pin of the material is left standing in the centre of the hole, as

FIG. 167.—The Drill.

FIG. 168.—The Drill.

shown in Fig. 169, which represents some small specimens of iron and steel actually drilled. In addition, cutting edges are provided at the

top of the drill, which give a conical shape to the top of the hole drilled. The hole, which takes about 10 minutes to drill in soft cast-

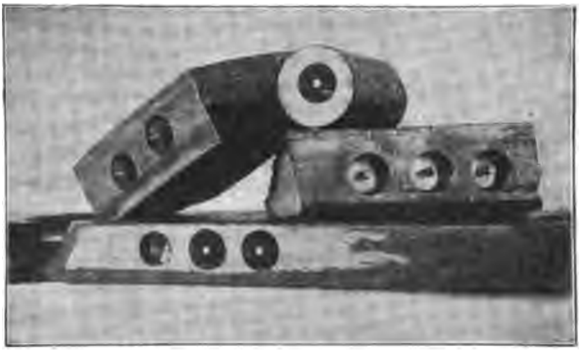


FIG. 169.—Drilled Specimens.

iron and 20 in wrought-iron or mild steel, is about $\frac{3}{4}''$ deep and $\frac{1}{2}''$ in its largest diameter, while the pin is $\frac{1}{10}''$ diameter. Such a hole may be drilled in any position where a bolt-hole is afterwards to be made, or otherwise in projections left specially for the purpose, which may be cut off the casting or forging on delivery and sent to the test-room.

FIG. 170.—The Plug Complete.

Before attempting to make a test with this complete magnetic testing set, it is necessary to place the apparatus on a rigid support as free from vibration as possible, and level by the screws provided at the base of the instrument. Then insert the plug tightly into the drilled specimen, and connect its leads according to the colours on the terminals. Lastly, see that the galvanometer is at zero. If not, remove the cover and slightly turn the milled head at the top. It is then possible to make one or more of the following determinations:—

Direct Permeability Test.—Set the battery key to DIRECT and adjust the resistance until H = 50. Next set the galvanometer key to the central position marked RESIS, and allow the galvanometer needle to come to rest.

Throw the battery key quickly over from DIRECT to REVERSE, and read the deflection on the scale marked *u* for H = 50. The value of B is also given on the corresponding scale.

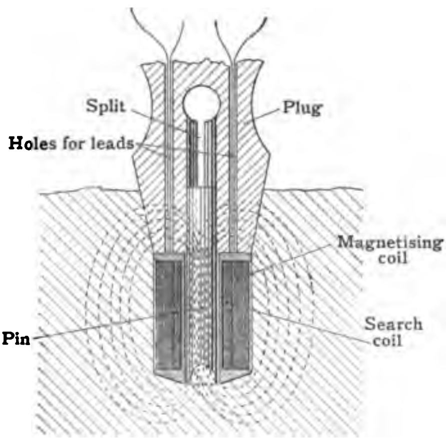


FIG. 171.—Section through Plug and Specimen.

To obtain the B-H Curve.—If the specimen has been previously magnetised, demagnetise it by reversals. For this purpose increase H to its maximum value and reverse the battery key rapidly and continually, bringing the resistance slowly back stop by stop to the lowest value. Keep the galvanometer key at RESIS, allowing the galvanometer needle to come to rest, then throw over battery key from DIRECT to REVERSE. The value of B is given by the galvanometer, while that of H is obtained from the other instrument. Repeat with successive values of H up to the maximum.

Retentivity Test.—Set H to any required value, and the galvanometer key to RESIS. Reverse the battery key and find B, as before. Let the galvanometer needle come to rest, then set the galvanometer key to REVERSE, and open the battery key; the swing gives the temporary magnetisation. Deduct this from the total magnetisation before obtained, and the result is the residual magnetisation.

To obtain the B-H Cycle.—Demagnetise by reversals as before. Set the galvanometer key to DIRECT, then make the battery key and observe the galvanometer swing and corresponding value of H. After the galvanometer needle has come to rest, alter the resistance suddenly by one or more stops and again take the swing. Repeat this until the maximum magnetisation is reached, after which the galvanometer key should be reversed and similar readings taken as the current is brought back step by step. The complete cycle can be taken in this way, the values of H being given by the ammeter as before, while the corresponding values of B are obtained by taking the sum of all the galvanometer deflections up to the required point. Examples of such observations are given in Dr. Drysdale's paper before the Institution of Electrical Engineers.

Magnetic Permeability Balance.—Without going into the descrip-

tion of the various methods [1] for accurately measuring the permeability of a specimen of magnetic material throughout a wide range of magnetising force, it may be said that nearly all are lengthy and tedious operations requiring considerable experimental skill. Moreover, manufacturers rarely need so great a range of measurement, one or two values of the induction, permeability, and magnetising force, at or near the usual working values employed in a given type of appliance, sufficing for their purpose. In view of these considerations and the fact that manufacturers are seldom in a position to make such difficult determinations themselves, Professor J. A. Ewing has devised a *magnetic balance* by means of which any one who has a reasonable amount of intelligence can rapidly and accurately measure

FIG. 172.—General View of Ewing's Magnetic Balance.

the permeability of any sample of material within the limits of induction-density used in practice.

The general appearance of the balance, complete, which is made by Messrs. Elliott Bros., of London, is shown in Fig. 172, while the principle of the arrangement of parts at the left-hand side, which are not too clearly indicated in Fig. 172, is shown in part perspective elevation in Fig. 173. The balance, which is of the traction type, consists of a coil C, of insulated copper wire, having a good soft-iron core I which terminates in the soft-iron end-cheeks F and E. One cheek F has its upper edge curved as shown; the other cheek E has a V-groove or notch in this upper edge. The specimen to be tested is in the form of a rod R, 4″ long, and turned accurately to a gauge of $\frac{1}{4}$″ in diameter. One end of this rod rests in the V-groove of E, the other end on the curved edge of F. A beam or scale-yard A is carried by two pivots P, one on each side of A, which rest on brackets B supported one on either side of E. Only one pivot and bracket is shown for clearness, but the line joining the pivot points passes through

[1] *Magnetic Induction in Iron and other Metals*, by J. A. Ewing; *Practical Electrical Testing*, by the Author.

the points of contact of R and E approximately. The rod R passes through a V-shaped stirrup S close to the pole-piece F, and which is carried by the left-hand end of A.

A balance-weight W slides along the beam A to the right of the pivots P, its position being read off on a scale D of equal divisions attached to the beam. The beam is capable of a small angular motion one way or the other about the pivots P, which act as a practically frictionless fulcrum, the play or motion being stopped by the bridge fixed to F and seen in Fig. 172. The base-board, Fig. 172, to which the arrangement indicated in Fig. 173 is fixed, also carries a variable rheostat of circular form seen next to the electro-magnet to the right. Next to the rheostat is a reversing switch, the handle of which can be moved into three definite positions, namely, *make*, *break*, and *reverse*. On the extreme right is a short pillar carrying a hinged piece which, when turned up, supports this end of the beam while the rod R is being taken out or put in. The electro-magnet coil, rheostat, and reversing switch are connected permanently in series between the two brass terminals shown just to the left of the short pillar. The only remaining piece of apparatus required is a small secondary cell, which is temporarily connected to these terminals at the time of a test.

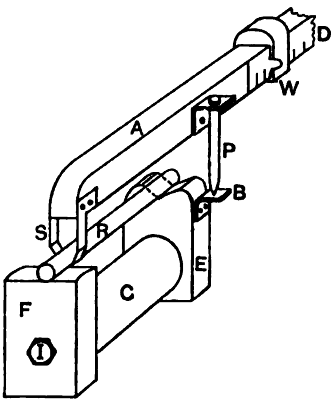


FIG. 173.—Principle of Ewing's Magnetic Balance.

The apparatus is so constructed that the electro-magnet exerts a magnetising force, with the bar or rod R in position, of $H = 20$ C.G.S. units. This value has been chosen because the B-H curves of different specimens (*vide* p. 142) often cross for much smaller values of H, *i.e.* their order of goodness changes when H changes. Professor Ewing has, however, found that in the region of $H = 20$ and over, the order of goodness is maintained, and, further, that $H = 20$ is a value at which there is a large difference between different specimens, and hence a comparison is all the more easy. From a large number of tests it has been found that for $H = 20$ the values of B vary from 16,000 in the very best magnetic material to 12,000 in poor material, and these have been made the limits of the range of the balance as seen by its scale. Owing to the way in which the beam A is pivoted, the side of the test-rod R touches the pole-piece F at one and the same point, only in a perfectly definite manner, whilst the other end

of R which remains in contact with the V-groove in E forms a sort of magnetic hinge. A standard rod, the induction-density in which has been carefully found by the most accurate method, when $H = 20$, is supplied with the bridge, and the method of making a test on any specimen is as follows:—

The standard rod is placed in position at R, and the slider-weight W set to read the induction, on the beam, which it is known to have when $H = 20$. The circular rheostat is then carefully turned until the leverage exerted by the beam detaches the end of the standard rod from the pole F. The electro-magnet must now be exerting a magnetising force of $H = 20$, so that the standard rod serves instead of an ammeter. The standard is next replaced by the rod to be tested, and with the same magnetising force of 20 W is now moved so that it is likewise just detached from F. The induction in it is then indicated by the position of W on the scale beam A. Thus the force requisite to detach the end of R from F is a measure of the induction B in the rod R for one constant and definite value of magnetising force H. The current is reversed two or three times, by means of the switch shown, after R is placed in position and before moving W, so as to wipe out residual effects due to previous magnetisation. The pole-pieces F and E and the rod R must be clean and free from dust and rust, and the scale on the beam is obtained by using standard rods having different inductions for the same value of $H = 20$ C.G.S. units. The user of this balance can therefore at once see what kind of a specimen he has as regards magnetic virtues, and in most cases this is all a dynamo or motor manufacturer wants to know. The balance has an advantage over others of like nature employing a traction principle, in that a perfectly definite contact between the cylindrically turned surface of the rod and pole is much more easily obtained than in cases where the rod is detached in an axial direction. The reliability of a balance such as this depends largely on the contact surfaces always being in the same condition and always touching at the same point. The ease and rapidity with which the balance can be manipulated, coupled with its extreme simplicity, makes it suitable for workshop use.

Instruments for measuring Magnetic Hysteresis.—The determination of magnetic hysteresis in a sample of magnetic material accurately, is a tedious operation attended with some difficulty, and calls for an appreciable amount of experimental skill on the part of the operator. The methods employed, *e.g.* the *ballistic* and *magnetometric*, cannot, however, be dealt with here; suffice it to say that before a measure of the power wasted in hysteresis can be obtained, the B-H

curve (cycle) (*vide* p. 146) must be plotted from the table of numerical results obtained in the test, and its area found. Of recent years special instruments have been devised with the object of enabling the hysteresis of any specimen to be found rapidly and with considerable accuracy by a single observation. Such instruments may be conveniently termed *hysteresis testers*, and the two most prominent forms are those devised by Professor Ewing and by Messrs. Blondel and Carpentier.[1]

Before going into the general arrangement of these two forms, it may be pointed out that the magnetic hysteresis exhibited by magnetic material varies in magnitude *for the same specimen* according to nature of the change in the magnetising force and to the manner in which it is applied. As measured statically, *e.g.* by the ballistic method, it has one value, which differs from the values obtained in both an alternating and rotating magnetic field and is smaller than either by some 7 %.[2] R. Hiecke[3] and A. Grau find that the hysteresis in a rotating field is almost exactly double the value found for the same specimen in an alternating field. The rotating field is the type of field met with in the armature of a continuous-current dynamo and polyphase alternating-current motors, while the alternating field is that met with in appliances using single-phase alternating current, as for instance the ordinary static transformer. It therefore becomes important to be able to measure the hysteresis of a specimen under conditions similar to those which it will have to work under in practice. This is accomplished in the so-called hysteresis tester.

Blondel-Carpentier Hysteresis Tester.—A general view of this instrument, complete, is shown in Fig. 174, but its construction will be better understood from a reference to the sectional elevation given in Fig. 175. It comprises a laminated, powerful permanent magnet M of U form, capable of giving a magnetic induction of about 10,000 C.G.S. lines. It is carried, with its limbs vertical, on a flat circular metal plate C, having a boss D which terminates in a fairly thin spindle. This spindle turns in a fixed boss E, and its end rests on the end of an arrestment-screw G having a tommy head and lock-nut N.

A main wooden base B, resting on three legs or feet F, supports the whole instrument. Through B passes radially a spindle L, terminating in a milled disc H at the edge of the base B. To the other end of L is fixed a roller disc K having a leather rim, whilst the protruding end of the spindle is reduced in diameter and has a bearing in the

[1] Armagnat, *L'Industrie Électrique*, 7. pp. 543-546, 1898.
[2] According to A. Dina, *Elettricità*, Milan, Sept. 28, Oct. 5 and 19, 1901.
[3] *Elektrotechn. Zeitschr.* 23. pp. 142, 143, Feb. 13, 1902.

boss E. When the instrument is being used, the weight of the magnet M is taken by the friction disc K at the point of contact of this and the disc C. Thus, turning H causes M to rotate by the friction drive between C and K. By slackening the lock-nut N and screwing up the arrestment-screw G, the magnet and its attached base disc C is lifted off and supported clear of the driving roller K and cannot then be turned by turning H. The driving mechanism should thus be put out of action at the end of every test and during transit. The poles of M are capped with an annular brass framing which carries two or three small rollers O. These rotate with this framing and roll on the fixed annular framing carried by the three pillars A, thus forming the upper bearing for the rotating magnet M.

FIG. 174.—Hysteresis Tester.

The test-piece or specimen I is prepared in the form of thin annular discs, 55 mm. in outside diameter and 38 mm. in inside diameter, being cut from the sheet to be tested and superposed on one another to a total thickness of 4 mm. These dimensions are essential, the specimen being cut or preferably turned to size rather than punched or stamped, which has the effect of hardening the metal. This test-piece I is centred upon and carried by a brass holder V, the vertical spindle of which (shown shaded) can turn freely in an upper pivot R and lower adjustable pivot-screw Y. This last-named is provided with a lock-nut and is carried at the bottom of the brass tube T, the upper end of which terminates in a hollow brass box Z. The box and tubes are carried by the fixed framing which is supported by the pillars A. The spindle is provided with a pointer P at the top and a controlling spring S at its lower end, which is immersed in thick oil to give the necessary dead-beat motion to the spindle and pointer P. The hollow graduated scale Q is integral with the ring which encircles the glass cover, and can thus be readily set round to adjust the zero as required. The laminated specimen ring I, which is secured to its brass holder V by little flat swivelling spring clips (not shown), is supported horizontally between the limbs or poles of the magnet M. To place a test-piece in position, the glass cover, upper bearing centre for the pivot R, and scale G, which form one piece, are removed, and then the index P. The brass holder and its attachments

are then lifted out by the milled flange W, the specimen I placed in position and secured by turning the three clips, and the various parts replaced in order, when the instrument is ready for use.

The rationale of the test is as follows:—When the permanent magnet M is rotated the magnetic induction through the test-piece I is continuously displaced relatively to the iron, and hysteresis gives rise to effects which are closely analogous to those of friction. These frictional effects cause the test-piece I to be dragged round in the

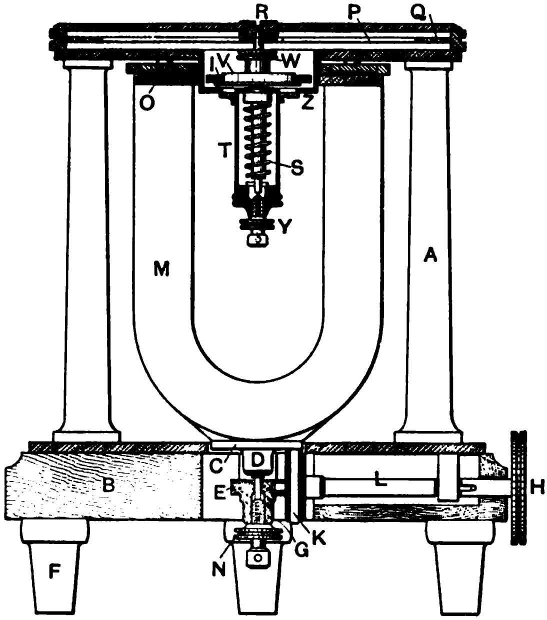


FIG. 175.—Sectional View of Hysteresis Tester.

direction in which M is being turned, a torsional effort being thus exerted upon the controlling spring. After a few moments the test-piece I and its system settle down into a position of equilibrium, in which the hysteresis-couple is just balanced by the opposing effort of the spring S. The force of torsion or opposing effort of the spring is proportional to the angle of torsion, and this angle is directly indicated by the pointer P on the scale G. It was pointed out on page 149 that the work done against hysteresis, in taking a specimen through a given cycle of magnetisation, is independent, within limits, of the rate at which the cycle is performed. If, therefore, the test-ring I is built up to the 4 mm. thickness with not less than four discs, the effect of eddy or Foucault currents in them is found to be quite negligible, and the hysteresis-

couple will be practically independent of the speed of rotation of M and directly proportional to the deflection of P. The hysteresis coefficient of any given sample of iron is determined from comparison with a standard test-piece the coefficient η_s of which has been very carefully found from independent measurement. With, say, the given sample in position, turn the wheel or head H sufficiently fast (two or three turns per second) to make the pointer P take up a steady position. Next turn round the glass cover and scale G until the zero is opposite P, the magnet M being in motion as above. Then turn the head H at the same speed in the opposite direction, and note the deflection D° of the pointer on the scale. Repeating these operations for the similarly formed standard in position in the instrument instead of the sample to be tested, and obtaining a corresponding deflection D_s, we shall have—

Coefficient of given sample $\quad \eta = \frac{D^\circ}{D_s^\circ} \times \eta_s$,

whence the loss due to magnetic hysteresis (p. 148) is

$$W_H = \eta B^{1.6} \text{ approximately.}$$

The method employed in obtaining the deflections by rotating the magnet in opposite directions successively has the advantage of doubling the sensitiveness of the instrument and also of eliminating any errors arising from the previous magnetisation of the iron samples. The results obtained with the instrument can in all cases be relied upon to within 5 %, though usually to 2 %, which is quite accurate enough for all practical purposes, seeing that the iron under test will not be found homogeneous to within such a small percentage, and that the index of B in the last relation is not a very definite and constant number.

The causes tending to introduce errors into the readings are:—

1. Weakening of the permanent magnet M with age; this source of error has been reduced to a negligible amount by only using magnets of the highest quality which have been carefully 'aged.'

2. The coefficient η_s of the standard specimen may change with age. Such changes are most liable to occur in iron whose coefficient of hysteresis is small, and for this reason the standard is made from iron having a moderate value for η, thus ensuring greater stability with time. The instrument has the advantage of being accurate, strongly made, and easily manipulated by any intelligent workman unaccustomed to testing.

From what has been said it will be seen that the Blondel-Carpentier hysteresis tester measures the kind of hysteresis met with in dynamo armatures, *i.e.* rotatory hysteresis. By using the specimen and

standard in the shape of similarly formed laminated rods instead of rings, the instrument will measure alternating hysteresis. In either case the air-gap between the magnet poles and the specimen is made sufficiently large to render the magnetic reluctance of the specimen negligible in comparison with it. The principle involved in the measurement of hysteresis by the above instrument is almost identical with that which Professor J. A. Ewing had previously introduced and used in his hysteresis tester.[1] The general forms of the two instruments are somewhat different, Professor Ewing causing his test-piece to rotate by turning a handle, the hysteresis-couple being measured by the angular displacement of the permanent magnet, which is controlled by gravity.

QUESTIONS ON CHAPTER VII

[*Supplement all Answers with Sketches when possible.*]

1. Describe the tangent galvanometer, and prove the relation that exists between the current and the deflection. (Ord. T. and T. 1897.)

2. Show by a sketch how you would connect up an energy meter, such as the Elihu-Thomson meter, on a 2-wire circuit. (Prelim. 1897.)

3. What is the difference, as regards construction and use, between an ammeter and a voltmeter? (Prelim. 1897.)

4. What forms of ammeters and voltmeters are likely to be affected by neighbouring current circuits,—for instance, those on a switchboard,—and what are the forms that are practically unaffected? (Ord. 1897.)

5. What are the special advantages and disadvantages of electro-static voltmeters as compared with current voltmeters? Describe in detail some form of electro-static voltmeter suitable for use in a central station. (Ord. 1897.)

6. Describe in detail a wattmeter for use on alternating-current circuits. What precautions must be taken in its construction, and what is the exact nature of the error likely to be met with in its use? (Hons. Sect. I. 1897.)

7. Give sketches illustrating the construction of a coulomb meter and an energy meter, each intended to be used on alternating-current circuits. What errors are to be looked for in such meters? (Hons. Sect. I. 1897.)

8. Describe a frequency meter; also some form of phase indicator for measuring the difference in phase between two alternating currents. (Hons. Sect. I. 1897.)

9. Give detailed sketches of a galvanometer, with all modern improvements, to be used for testing the insulation of somewhat short lengths of well-insulated cable. (Hons. Sect. I. 1897.)

10. Describe in detail a voltametric method of calibrating an ammeter, and a potentiometer method of calibrating a voltmeter, and draw attention to the precautions that must be taken to secure accuracy. (Hons. Sect. I. 1897.)

11. What is the nature of the error produced in an electro-magnetic voltmeter used on an alternating-current circuit if the frequency be changed? How can this error be partly compensated for? and mention any types of voltmeters, should such exist, which require no such compensation. (Hons. Sect. I. 1897.)

12. Describe a commercial ohmmeter, with sketches, and explain how it is used.

[1] A full description of this instrument will be found in the *Jour. Inst. E.E.* vol. 24. pp. 398-430 (1895).

In drawing up a specification for the wiring of a private house, what standard of insulation resistance would you require, and what maximum drop of pressure would you allow? (Hons. Sect. III. 1897, and Prelim. 1903.)

13. Describe a method of determining the volume of current in a circuit, with the aid of a voltmeter and a series of known resistances, but without the use of other measuring instruments. (Hons. Elec.-Metall. 1897.)

14. Describe, with sketches, some form of moving-coil voltmeter. What are the advantages of this type? (Ord. 1898.)

15. Describe a good form of voltmeter for use on an alternating-current system. (Ord. 1898.)

16. What are the most important errors to be looked for in consumers' meters? (Hons. Sect. III. 1898.)

17. Describe a potentiometer suitable for measuring from 10 to 1000 amperes, and give a sketch indicating the principal dimensions. (Hons. Sect. I. 1898.)

18. Compare the advantages and disadvantages of slide-wire, dial, and P.O. pattern Wheatstone bridges. (Hons. Sect. I. 1898.)

19. How does the construction of an ampere-hour or quantity meter differ from that of a volt-ampere-hour or energy meter? Give a sketch of a good specimen of each type. When can one be used in place of the other? Have you any suggestion to make with reference to the name 'recording wattmeter' as applied to the Elihu-Thomson supply meter? (Hons. Sect. I. 1898.)

20. Describe, with sketches, some form of accurate portable testing set used for measuring the insulation resistance of an electric light installation. (Prelims. 1899 and 1900.)

21. How does a voltmeter differ from an ammeter in its construction and use? What sort of resistance may be given to a voltmeter used with a single accumulator? (Prelim. 1899.)

22. Describe, with rough dimensional sketches, a good form of standard resistance having a value 0·001 ohm, and explain how it is used in the measurement of large currents. (Ord. 1899.)

23. Describe the platinum thermometer, and explain, with diagrams, how it may be used with a slide-wire Wheatstone bridge so that uniformly distant scale readings shall be directly proportional to the temperature measured. Why are dummy leads provided, and how are they used? (Hons. Sect. I. 1899.)

24. What are the relative advantages of the moving-needle and the moving-coil galvanometers for the measurement of very small currents. (Hons. Sect. I. 1899.)

25. Describe, with sketches, the apparatus required and the method employed for measuring the permeability and the hysteresis of (*a*) an iron rod, (*b*) a transformer core-plate. (Hons. Sect. I. 1899.)

26. Given a sensitive milliammeter of low resistance, design a set of resistances which will enable it to be used as a voltmeter to measure up to 1000 volts; as an ammeter, from 1 to 100 amperes; and as a direct-reading ohmmeter on a constant-pressure supply current. (Hons. Sect. I. 1899.)

27. Describe the construction and use of a wattmeter, and state the important points to be attended to if the wattmeter is to be used on an alternating-current circuit. (Ord. 1900.)

28. What special arrangements, if any, must be employed with (*a*) an electro-magnetic voltmeter, (*b*) a hot-wire voltmeter, (*c*) an electro-static voltmeter, when they are used on alternating-current circuits? Have you any reason for adopting one of the types rather than the other two? if so, explain it in full. (Hons. Sect. I. 1900.)

29. Give sketches illustrating the full details of the construction of hot-wire and electro-static voltmeters. What kind of errors would you look for in testing these two types of instruments respectively? (Hons. Sect. I. 1900.)

30. Describe, by means of sketches, the details of the construction and method of application of a motor meter for measuring the energy supplied to a house on a direct-current three-wire system. (Hons. Sect. I. 1900.)

31. Give sketches showing the details of the construction of a potentiometer for general use, and explain exactly what measurements can be made with the apparatus you describe, and state with what degree of accuracy the results can be obtained. (Hons. Sect. I. 1900.)

32. What is the difference between a Thomson and a D'Arsonval mirror galvanometer, and what special advantages do each possess? (Ord. T. and T. 1900.)

33. What is a wattmeter, and what does it measure? Give sketches showing some form of wattmeter suitable for use in a workshop. (Prelim. 1901.)

34. Illustrate, with drawings, the construction and action of a direct-reading magnetic-field tester. Give examples of the use of such an instrument in practice. What errors would you look for if you were testing its accuracy? (Hons. Sect. I. 1901.)

35. Explain in detail how a dynamometer wattmeter may be compensated for the loss in its pressure coil. (Ord. 1902.)

36. Describe any moving-coil ammeter with which you are acquainted. What advantages has this type over soft-iron and hot-wire instruments? (Prelim. 1902.)

37. What are the essential features of a good house meter? Describe the Thomson energy meter, and show that the number of revolutions is proportional to the energy used. Why is it incorrect to call this instrument a 'recording wattmeter'? (Ord. 1903.)

38. What is an oscillograph, and what are its uses? Describe any form with which you are acquainted, giving full particulars as to the conditions necessary to ensure reliable results. (Hons. Sect. I. 1903.)

39. Describe in detail, with sketches, any wattmeter of the 'induction type' suitable for three-phase extra high-pressure circuit with which you are acquainted. Discuss the sources of error and their approximate magnitude in this type, and state how they are affected by the power factor of the circuit. (Hons. Sect. I. 1903.)

40. Describe in detail the Kelvin current balance, and state what precautions have to be taken to ensure that balances for large currents should read correctly on alternating-current circuits. (Ord. 1904.)

41. Describe any alternating-current energy meter suitable for large powers (say 1000 amperes and 200 volts) with which you are acquainted, and explain how you would test the accuracy of such an instrument on an inductive circuit. (Hons. Sect. I. 1904.)

42. Describe in detail, with sketches, any hot-wire ammeter with which you are acquainted, and state exactly in what respects such an instrument differs from a voltmeter of the same type. (Prelim. 1904.)

43. (*a*) Explain the principle of an 'astatic' galvanometer; (*b*) What is meant by a 'ballistic' galvanometer? and (*c*) For what class of tests is it useful? (Hons. Teleg. 1904.)

CHAPTER VIII

ELECTRIC INCANDESCENT LAMPS

PROBABLY no subject has, up to the present, received more wide-spread attention than that of the production of light by electricity. It is true that the most striking development of commercial appliances for effecting this object has taken place in the past few years, and the result, illustrated by the electric lamp of the present day, has been attained by much labour and in many stages of perfection. Electric lamps in their present stage of development may be broadly classified as follows: *Incandescent* lamps, *Arc* lamps, and *Vapour* lamps. In each, the light produced is the result of a transformation of energy under conditions in which, *up to* a certain point, heat is absorbed in certain matter more rapidly than it is given out or radiated, thereby causing a rise of temperature. At this point the energy dissipated in a given time is equal to that received in the same interval of time, and the temperature then remains constant. If the temperature is sufficiently high, some of the electrical energy so received will be transformed into light rays, the remainder into invisible heat rays. The proportion between these heat and light rays will depend on the relation of the conductivity of, and the medium which pervades, the matter in which the electrical energy is absorbed, to the amount of this energy. It is unfortunate that the proportion is so large (the light rays being usually a small fraction only of the heat rays); for the efficiency of any lamp as a light-emitting source is represented by the ratio of the energy re-appearing in the form of luminous rays to the total energy given to the lamp. This optical efficiency,[1] as it may be termed, although higher than in many other sources of light, is at the best low, amounting to something of the order of 6·0 to 7·6 per cent in the ordinary incandescent class of lamp. It is, however, higher in the arc lamp, and higher still in the vapour lamp.

[1] 'Investigation of the Radiation from the Newer Glow-Lamps,' by W. Vöge (*Biebl. Ann. d. Physik*, 28. 21. pp. 1136-1138, 1904).

From the foregoing remarks, applicable to lamps in general, we may pass on to a consideration of the different classes of lamps, and take them in the order mentioned above.

Incandescent Lamps.—Space will not permit of even a reference to the history of such lamps; suffice it to say that the first practical attempt to produce one was made as early as about 1840. Since then, a vast amount of attention has been devoted by different scientists to the production of such an appliance, with the result that we now possess a so-called incandescent or glow lamp which, while not quite as efficient as can be desired, nevertheless fills a long-felt want and is a commercial success.

The principle on which the action of these lamps is based is the heating effect of a current of electricity flowing through a conductor (*vide* p. 54 *et seq.*). We have seen that the energy expended in t seconds in a conductor of resistance R ohms carrying a current of A amperes is

$$A^2Rt \text{ joules,}$$

or, if $J =$ Joule's equivalent (p. 55), the amount of heat (H) produced is

$$H = \frac{A^2Rt}{J} \text{ units.}$$

Thus it is seen that for a given current the amount of heat produced per second depends on R; and the greater this resistance is, for the same conditions, the greater the amount of heat produced. The trend of research, then, has been to find a material which, while having a considerable specific resistance (p. 69), was also very refractory in nature, and hence capable of withstanding the very high temperature to which it must be raised in order to emit luminous rays in addition to heat rays. The materials which have been tried in the now well-known ordinary form of glow-lamp are platinum, osmium (see p. 317), iridium,[1] thorium, an alloy of platinum and iridium, titanium carbide, and carbon. Of these, practically carbon only has survived the trial, and is now universally employed for the filaments (*vide* p. 297). The reasons for this choice are:—

Firstly, that with carbon (which is a non-metal), after the temperature of incandescence is reached, the luminous rays increase more rapidly, as compared with the non-luminous or heat rays, for further rises of temperature than is the case with the metals.

Secondly, in addition to carbon giving a better optical efficiency, its temperature of volatilisation is higher than that of metals, and hence it can be raised to a higher temperature than they can. This is an

[1] *Sci. Amer.* 91. p. 338, Nov. 1, 1904.

extremely important advantage, for the optical efficiency of a light-emitting source depends very materially on the temperature. For example: an increase of 15 per cent in the temperature of a luminous source near the point of volatilisation may produce an increase amounting to as much as 30 or 40 times (*i.e.* 3000 to 4000 per cent) more light. In the case of metals, the temperature at which they emit light is not much less than that at which they fuse, whereas carbon has no actual fusing-point—only a region of volatilisation for temperatures higher than that needed for ordinary bright incandescence.

Thirdly, the sectional area of carbon can be made more uniform than is possible with that of metallic wires. This is an extremely important consideration, as will be seen presently, and materially helped the decision in favour of carbon.

Manufacture of Electric Glow-Lamps.—Passing on now to the construction of electric incandescent or glow lamps. Comparatively few people, out of the very large number who use these lamps, have, doubtless, any idea at all of the intricate nature of, as well as the skill and experience required in the manufacture of, this apparently simple appliance. They would, however, soon be undeceived if they knew that this simple-looking lamp, comprising merely a glass bulb fitted with a brass cap outside and the conducting thread or filament inside, was the object (from first inception to completion) of between thirty and forty distinct processes or operations, most of which are of a most intricate and delicate nature.

The Filament is of course the chief feature of an electric glow-lamp, its composition and evolution very materially affecting the ultimate behaviour and success of the lamp. In all cases the filament is now made from cellulose—a more or less transparent, gelatinous hydrocarbon giving a better efficiency and having a longer life than the original filaments made from bamboo. Different makers prepare their cellulose in different ways, as follow :—

1. Heating the purest cotton wool obtainable with a solution of zinc chloride (in which it dissolves) in a suitable vessel; the solution, in the form of a thick syrup when cool, being decanted and then ready for use. This is a very commonly used method nowadays.

2. Treating special kinds of paper chemically in such a way as to produce a thick plastic solution of cellulose.

3. Treating the purest cotton wool to a combined washing and boiling operation in distilled water in order to remove any 'dressing,' dirt, or other foreign adherent accruing in the course of its manufacture. After being dried, it is wound loosely backwards and forwards round two opposite sides of a rectangular glass frame of such a

size that each ply is a little longer than the length which the finished filament is to have and does not touch any other ply. The glass frame, thus wound with this prepared cotton, is next immersed in a *clear* solution consisting of concentrated pure sulphuric acid and pure water in the proportions of 2 : 1, the temperature of which should be 15° C. This operation, which takes only a short time, is complete when the last traces of the strands in the cotton disappear, the frame then being immediately taken out and reimmersed for some hours in a stream of clean cold water. It must next be immersed in a bath containing a 1 per cent solution of ammonia and water to neutralise the last traces of acid, and finally again in the stream of water. The thread (as we may term it) so formed has now quite a different appearance from that of the original cotton, having been converted by chemical action into the transparent, gelatinous substance—cellulose.

The next operation is to cause the thread to assume the desired form of filament while still wet and in a pliable condition.

In the case of methods 1 and 2 above, the thread is obtained by forcing the cellulose solution, under pneumatic pressure, through orifices or dies. These consist of sapphire-agate stones mounted at the end of the tubes leading from the cellulose reservoir, and which contain holes of various diameters corresponding to the cross-sectional area of filament required. The cellulose issues from the dies in a continous thread, and coils itself into tall glass jars filled with spirit such as wood alcohol or other setting solution, which sets and hardens it. After remaining in this solution for a sufficient time to get rid of the remaining traces of zinc chloride (in some cases three or four days), the thread, which now resembles fine catgut (being clear, tough, and flexible), is treated with water or chemicals, and in all cases finally for several hours to a stream of water to get rid of all traces of such chemicals, after which it is dried. Simple as the process up to now appears to be, great care has to be taken in obtaining exact proportions of ingredients in solutions and mixtures. The temperature of these together with the forcing pressure at the dies for a given diameter of thread have to be carefully maintained in order to ensure success.

Shaping the thread is an operation which presents no difficulty, and in methods 1 and 2 is effected by winding the prepared thread over carbon blocks or 'formers' shaped to the desired form of filament. In method 3 this winding is done while the thread is still wet from the final washing operation, it being previously cut from the frame into the several plies, only at the points where it touches the opposite sides of the dipping-frame round which it is wound. In

this way a uniformity of texture is ensured throughout each ply which goes to form one filament.

Carbonising the Thread. — In methods 1 and 2, the carbon 'formers' thus wound with the thread, and in 3 only the 'formed' threads, which (when dry) have been cut off the former, are packed all round with powdered carbon or plumbago in iron or graphite crucibles. Considerable care has to be taken to ensure the air around the blocks and thread being displaced by the powder, thus preserving them from oxidation when heated. The crucibles are next placed in a coke furnace and very slowly brought up to the highest temperature obtainable (a white-heat), at which they are kept for a day or two, when the furnace is then allowed to die out and the crucibles become cold. The filaments, for such we must now call them, when taken out of the crucibles will now have been converted from the original cellulose into pure carbon, and should be of a good semi-dull black colour throughout.

In methods 1 and 2 they are next cut from the 'formers,' and in all cases, by whatever route this individual filament form has been arrived at, they should be very hard and show considerable elasticity. If they are variously glossy and dull in colour, or irregular in thickness, for the carbonising process causes them to shrink, they are discarded, air having probably found its way into the crucible during the process and spoilt them. Some lamp manufacturers do not make their own filaments, but buy them in assorted sizes in this condition and stage of production.

The filaments are next carefully sorted into different diameters (from about 0·0014 in. upwards in steps), according to the known relationship of candle-power and voltage to diameter of filament. The diameter is measured by micrometer calipers to $\frac{1}{10000}$th of an inch, and the free ends are snapped off to the right length on a corresponding gauge.

Mounting the Filament.—This operation, which comes next, consists in attaching the free ends of the filament to the two platinum or other 'leading-in' wires. As the method adopted for doing this, together with the form of support for the wires, differs slightly with each manufacturer, a general indication only of the principle used by the best makers will be given.

Referring to Fig. 176, a piece of glass tube T is taken and a lip L formed at one end. Two short lengths of thin platinum wire AK, AD, cut the exact length from a reel by a machine (at the rate of many dozens per minute) which simultaneously flattens one end as indicated at K, are firmly jointed to two rather thicker copper wires

C. The pair of compound wires CK, CD are then held apart inside the tube T, together with two additional platinum wires S in the case of high-voltage lamps with 'anchored' filaments, while the tube is heated to softness and the end B then squeezed with pliers. This not only seals the joints A A just inside the glass bead B, but also an appreciable length of the platinum wires AK and AD.

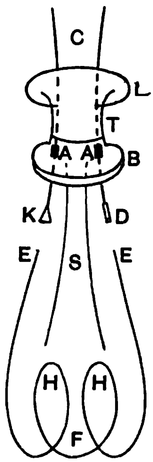


FIG. 176.—Sealing-in Bead and Detached Filament.

Costly as platinum is (about £4 per ounce), it is the only material which has been successfully used until quite recently, owing to it having the same coefficient of thermal expansion as glass, and being unaffected by the heat of the blowpipe. Both are vital properties, especially the former, since with nearly all other metals the heating of the lamp would cause unequal expansion of the glass bead B and wires AK, AD, and result in the fracture of the bead. Recently, however, A. Bainville (*Électricien*, 26. pp. 114-5, Aug. 22, 1903) and C. E. Guillaume (*Électricien*, 27. p. 31, Jan. 9, 1904) described the employment of nickel steel for 'leading-in' wires in place of platinum, and which is rapidly extending. The alloy can be chosen so as to have the same coefficient of dilation as the glass into which it is fused.

The flattened ends, such as K, are then passed through a die which forms them into tiny cups, as indicated at D, into which the free ends E of the filament F are eventually pushed. These junctions, which naturally attain a very high temperature, have given considerable trouble in the past on account of the heat, so that two or three methods of making the joint complete have been devised. The first to be employed commercially consisted in cementing the ends E and D with a thick paste made of very finely ground charcoal, distilled water, together with coarse sugar or starch in just sufficient quantity to bind the charcoal into a paste. The cemented joint was dried slowly, and was finally completed in the next operation.

The method now commonly employed consists in inserting the ends E in the cups D and then pinching the joint with pliers. As this, however, would not be sufficient, the filament is short-circuited by a special bridge at the junctions and then, together with these joints, is immersed in a fluid hydrocarbon, often benzoline or benzene, which is rich in carbon and easily decomposed by heat. A suitable current, sufficiently strong to make the junctions, such as D, glow, is

then passed through them while in the fluid, resulting in the deposition of carbon, out of the fluid, all round the junctions. When this has gone on to a sufficient extent, the arrangement is taken out and a solid, compact, efficient joint obtained. The supporting wires or *anchors*, such as S, in the case of long-filament high-voltage lamps, are next hooked round the loops at H, H, and the filament with its attachment is then ready for the next operation.

'Flashing' Process.—This is an indispensable and most important operation in the manufacture, for on it depends the life and efficiency of the lamp. The object of it is to

(*a*) Coat the carbon filament with a thin layer of very hard finely divided carbon, thereby reducing its initial resistance (always very high) to any desired amount;

(*b*) Make the filament of perfectly uniform cross section throughout.

The principle involved in the operation of *flashing* consists in raising the filament to a high degree of incandescence while in an atmosphere of some hydrocarbon vapour. The cross section of the filament not being uniform, for the pores in it as well as the unevenness can easily be seen under a microscope, the thinner portions become much hotter than the rest, causing the carbon in the vapour to be deposited in much greater quantity at such points, as well as in every little microscopic hole, thus making the section uniform throughout. The want of homogeneity in the unflashed filament is due to the other constituents of cellulose being driven off in gaseous form during the carbonising of the filament, leaving only pure carbon behind.

The arrangement employed in flashing differs somewhat in different factories, while the hydrocarbon employed is ordinary coal gas, benzene, or some special hydrocarbon, which in many cases is a trade secret. The general principle of the arrangement used, but not its precise form, may be gathered from Fig. 177, in which V is a strong, clear (though preferably coloured) glass vessel, having a rather wide rim on which rests a thick glass plate or lid L. The contact surfaces are well ground to ensure a good fit, or rubber packing is used instead for making an air-tight junction, and the lid carries two terminals T, which are provided with metal rods or spring clamps D. A tube P with a tap A connects the vessel V with a quick-acting air-pump for exhausting V, while the tube Q with a tap B connects to the source of hydrocarbon. In some cases only one pipe to the flashing-jar V is used, this connecting through a two-way cock to the sources just named. So that the handle placed in one position evacuates, and in

the next admits, the vapour. Two holes in the stalks D admit of the glass bead with its attached filament F being quickly hung up inside the vessel by the 'leading-out' wires C as shown. The terminals T, and hence the filament, are connected in one arm R of a Wheatstone-bridge arrangement, the remaining three arms, r_1, r_2, r_3, being previously adjusted so that balance and no deflection on the sensitive galvanometer G is obtained only when F has the desired resistance. The E.M.F. E used consists of a dynamo or battery of secondary cells giving from 150 volts upwards, the current being controlled by a multiple-block variable rheostat H*s*.

The operation of flashing is then as follows: With a filament

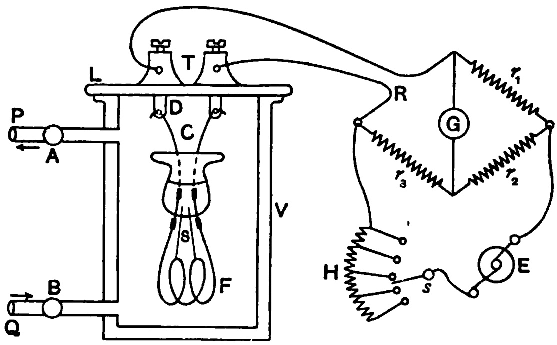


FIG. 177.—Connections and Arrangement of Flashing.

hung or clamped by suitable spring clamps in position, and using coal gas or benzene vapour, B is shut and A opened, when V is then exhausted of air. A is next shut and B opened, when V is at once filled with the hydrocarbon vapour, which rapidly evaporates owing to the low pressure inside. In some cases the vapour is obtained by sprinkling a few drops of a special hydrocarbon liquid into V by a brush through the top, B being kept closed. V is now exhausted through P and the open tap A, which is then closed, and nothing but the vapour fills V. In all cases the air is first carefully extracted from V to avoid explosions, and when V is full of nothing but the carbon vapour, *s* is closed and F brought up to bright incandescence by adjusting H and *s*. The galvanometer needle G is now hard up against the stop, and at the instant when it again arrives at its original zero, *s* is opened. Some makers employ an automatic cut-out for breaking circuit, as at *s*, when the filament reaches the desired resistance.

The filament F is now coated to a uniform thickness throughout with an extremely finely divided, hard, compact pure carbon, which fills

every microscopic hole and, moreover, has the required resistance for the given candle-power desired. The filament of a 100-volt 16-c.p. glow-lamp absorbing 3 watts per candle is about 0·12 mm. in diameter and 200 mm. long. Its resistance hot is about 208 ohms, and cold about 116 ohms. The filament of a 200-volt 16-c.p. lamp of the same efficiency would be from 350 to 400 mm. long. Some makers use unflashed filaments, which, having a higher specific resistance (ranging from 3500 to 5000 microhms per cm. cube), enable a 200-volt filament to be enclosed in the standard 100-volt lamp-bulb. Tests have shown that such filaments of 16-c.p. lose some 40 per cent of the c.p. and 30 to 40 per cent in efficiency in the first 600 hours of use. This loss of c.p. and efficiency in flashed filaments (which are less volatile and are stronger) is much less, and hence the best makers use such filaments and employ a larger bulb to take the longer filament consequent on the diminished specific resistance (about 2500 microhms per c.c.) due to flashing.

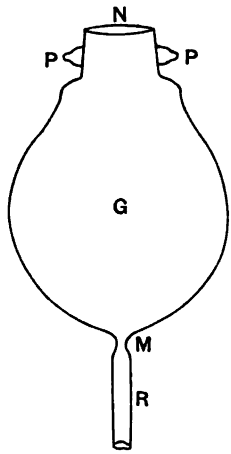


FIG. 178.—Lamp Globe.

The colour of the filament has now changed from black to a steel-grey colour, and it is ready to be inserted into its containing-globe. This glass globe G (Fig. 178) is blown to gauge from tubing, and has an open neck N at one end provided with two projections P, P at the side. The other end is drawn down to a fine bore M, to which is fused an enlarged stem R for attachment to the air-pump. The flashed filament F, with its glass bead B, is next inserted through the neck N of the globe G, and the lip L (Fig. 176) fused to N with a good air-tight joint. The arrangement is then ready for the next operation, namely, exhausting the globe G.

Evacuating the Lamp-Bulb.—Many difficulties attending this extremely important part of the manufacture of an electric glow-lamp have, by experience, been either overcome entirely or minimised of recent years. It is of the utmost importance to obtain a sufficiently good vacuum inside the bulb, for the poorer the vacuum the shorter will be the life of the lamp and the smaller its efficiency. The diminution in the life occurs through the more rapid disintegration or volatilisation of the filament as evinced by the more rapid blackening of the inside of the globe through the deposition of carbon on it. The diminution of efficiency with a poor vacuum occurs by reason of the increased facilities for the conduction of heat from filament to

globe and thence to the atmosphere, so that a given absorption of electrical energy does not result in such a high filament temperature, and therefore also in not such a large proportion of luminous energy.

The exhausting of the bulb is effected by an air suction-pump, various types of which are in common use, namely :—

The *Fleuss* or *Geryk* double-acting plunger mechanical air-pump.

The *Sprengel* mercurial air-pump.

The *Barr and Stroud* rotatory mercurial air-pump.

As it will be more convenient to give the construction and action of these pumps a little later on, we may briefly remark here that the lamp-bulb is connected to the air-pump used by the only remaining inlet or outlet, namely, the glass stem R. Usually several (six or more) lamps are exhausted in one operation, each having its stem R fused, in an air-tight joint, on to the *connection-tube* of the pump. The pump is then started, the outside of the bulb being played on all over by a hand-moved bunsen-burner for the purpose of assisting the pump by expanding and driving off residual air and vapour. When the vacuum has reached a steady value, the filament is raised just to redness, and from this condition, very slowly, to some 30 per cent above full incandescence, thereby ensuring a more perfect vacuum by driving off all gases occluded in the filament or other wires, the pump being kept going all the time.

The vacuum should now be sufficiently good, and the portion of the stem M being carefully softened by a blowpipe flame, the lamp is pulled carefully off the stem R and the current then switched off. The stem at M must be only just sufficiently softened to allow of the bulb being pulled away, otherwise the pressure of the outside air will cause an entrance at this point and the vacuum to be spoilt. The lamps next undergo a photometric test in which the candle-power together with both watts and voltage absorbed are determined, and by which the lamps are classified and sorted. They are now ready to be *capped*, which operation will be more readily understood from a reference to Fig. 179.

The Cap consists of a piece of brass tube M about $\frac{3}{4}$ in. long and $\frac{7}{8}$ in. diameter, into the upper end of which is pinned a disc of vitrite, porcelain, or some other hard-setting insulating material Q capable of standing heat and damp. Two thin plates of brass R, of either oval or sector shape, are let into Q flush with its surface, being held mainly by little lugs W on R. Two brass pins V are let into the tube M at opposite sides about $\frac{1}{4}$ in. from the surface Q, and in some cases these serve also to fix Q in the tube M, the main object of them being, however, to support the lamp when inserted in its holder (Fig. 181).

In mounting the cap on the lamp-bulb, the leading-out wires C (Fig. 177) are pushed through small holes drilled in R, a cement such as plaster of Paris or other hard-setting material capable of standing heat and damp (shown shaded in Fig. 179) being used to fill up the space between the bulb and tube M. This, when set, securely fixes the cap, while the glass projections P on the lamp prevent the cap being twisted off in the operation of inserting and withdrawing the lamp from its holder. The ends of the wires C are next bent over into a little groove in R and soldered flush with the surface.

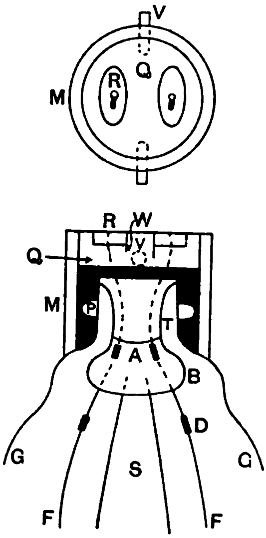


FIG. 179.—Lamp-Cap (Plan and Section).

The cap of the lamp (Fig. 179) is made entirely of vitrite, which is not only extremely hard and a good insulator for high voltages, but is unaffected by acid or other fumes.

The lamp again undergoes a photometric test for relative candle-power, voltage, current, and watts per candle-power, the first two together with the trade-mark being etched on the bulb by hydrofluoric acid when the lamp is ready for sale after it is cleaned.

It may be mentioned that many makers make an additional test, before *capping*, to that already named in order to see if the vacuum is good. This consists in passing a discharge from an ordinary Ruhmkorff induction coil through the bulb in the photometer dark-room. The tint of the *electro-static glow* obtained, which is similar to that obtained in a highly exhausted radiographic tube, forms the test of the perfection of the vacuum.

Enough has now been said about the manufacture of an ordinary electric glow-lamp to show the reader what a complex process it is. It should, however, be remembered that only the principal operations in the course of manufacture have been explained. Many minor operations and tests take place in addition, and considerable care, attention, and precautions are taken to ensure the production of a successful lamp and to avoid accidents in its manufacture. Space, however, will not permit of these little points being explained, and we will therefore give some illustrations of the forms taken by finished lamps.

Forms of Glow-Lamps.—Fig. 180 illustrates a lamp made by the Robertson Incandescent Lamp Company for use on 200-volt circuits,

and supplied by the General Electric Company, of London. It will be noticed that the double-looped filament is anchored by two stays, so that, notwithstanding it being so delicate, it cannot droop or short-circuit if the lamp is used in a horizontal or oblique position.

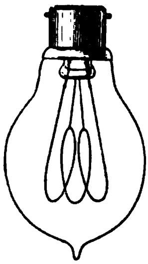


FIG. 180.—High-Voltage Lamp.

The maximum diameter of the bulb of this lamp = $2\frac{1}{4}$ ins., while the over-all length from sealing-off nipple to the top of the cap is 4 ins. For lamps of higher candle-power, up to and including the 50-c.p. lamp, the same general form is maintained, but the size slightly increases.

The candle-powers of lamps made, stocked, and used for ordinary lighting work by almost all makers are 8, 16, 25, 32, 50, 100, and upwards to 2000 c.p. at any pressure from 50 to 250 volts. Certain standard pressures—*e.g.* 100, 110, 200, and 220—are, however, most generally in operation; and lamps for pressures below 150 are called *low-voltage lamps*, those for pressures above, *high-voltage lamps*.

A lamp having a somewhat different arrangement of filament is shown in Fig. 181, and is known as a *reducing lamp* or *night-light lamp*. The longer of the two filaments is the normal one of the lamp, and gives 16 c.p. at 100 volts; but should a smaller c.p. be required, then instead of inserting an uneconomical resistance in circuit with the lamp to diminish its luminosity, the shorter filament can easily be put in series with the longer one by slightly turning the lamp in the special lamp-holder shown, so that the pins in the lamp-cap engage in the first notches seen in the holder (as seen in Fig. 181 they are engaging in the second notches, whence the longer filament would be alight). The effect of this is to almost extinguish the light from the longer one, while the short one glows at full incandescence ($2\frac{1}{2}$ c.p.) almost as economically as the longer one did at 16 c.p. A great saving of electrical energy can thus be effected with such a lamp. These lamps are also made for reducing from 8 c.p. to $2\frac{1}{2}$ c.p. and for 200-volt circuits. The most economical arrangement is obtained when the auxiliary lamp-filament takes half the P.D. of the mains at full incandescence.

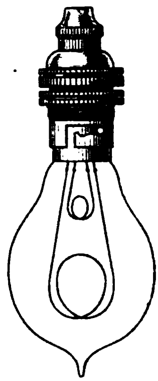


FIG. 181.—Two-Filament or Night-light Lamp.

Another arrangement of filaments shown in Fig. 182, and made by the Robertson Lamp Company, is employed in lamps used for *ship side-lights* in order to conform with Board of Trade Regulations. Two totally distinct but similar filaments, usually of 16 c.p. each, are

arranged *in parallel* in a common bulb. Thus, if one breaks from any cause the other remains intact, so that the permanence of the light does not depend on one filament.

In order to avoid having to anchor the filament of a high-voltage lamp (*e.g.* one for 200 volts, say) some makers employ two separate 100-volt filaments *in series* side by side in the bulb. Fig. 183 shows this arrangement in a well-known make of lamp, viz. *the Robertson*, where each filament gives 8 c.p. at 100 volts.

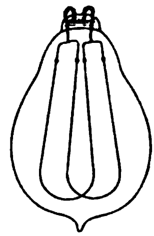


FIG. 182. — Ship Side-Light Lamp.

Within the last few months Messrs. Veritys Limited have acquired the sole agency for a new form of lamp called the 'Aston Bohm light.' It consists of an ordinary B.C. lamp-cap, a combined opal reflector and magnifying-lens bulb of special design, and a specially manufactured and shaped filament inside the exhausted bulb. Its useful life is said to be between 700 and 800 hours, and the actual c.p. in a vertical direction from 55 to 60. Since the ordinary 16-c.p. 60-watt lamp only gives a vertical c.p. of about $7\frac{1}{2}$, this new lamp will give a vertical illumination equal to about 8 of the ordinary type. A saving of 60 per cent in the cost of energy and a very large increase in efficiency is claimed, but it must be remembered that the illumination is in the form of a directed beam of light on a reduced area. This will, no doubt, be convenient in many cases, but since the lamp consumes 150 watts with a c.p. of 60 as a maximum, the commercial efficiency is only $\frac{150}{60} = 2\frac{1}{2}$ watts per candle, and therefore no greater than that of an ordinary glow-lamp.

Another form of lamp, made by nearly every maker, and used a good deal for street lighting as well as for other purposes, is that shown in Fig. 183. It has a detachable opal glass reflector which slips over the cap and rests on the bulb. Two separate low-voltage filaments are connected *in series* to give a high-voltage lamp for 200 to 250 volts, and the light is much more concentrated in a given direction with them than from those with clear bulbs.

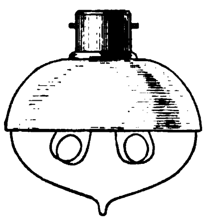


FIG. 183.—Lamp with Opal Reflector.

High-candle-power lamps (up to 2000 c.p.) were originally introduced by the Sunbeam Lamp Company, who still are the largest makers of them. They are now made by almost every maker, and are larger and more efficient than the smaller lamps. Fig. 184 shows a 200-volt 300-c.p. lamp with two filaments *in series*, and anchored in the manner shown. Though less efficient than the so-called arc lamp, they are sometimes to be preferred to these

for illuminating halls, etc., owing to the softer colour of the light and to them requiring no attention. The largest electric incandescent lamp is supposed to have been made by the Bryan-Marsh Company for lighthouse work (vide *Amer. Electrn.* 11. p. 340, 1899). It had a c.p. of 5000: two filaments in parallel, taking 236 volts and 3 watts per candle. The fog-penetrating power of such a lamp is much superior to that of an arc lamp.

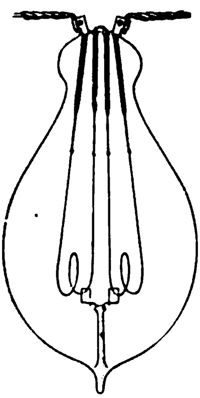


FIG. 184.—High-Voltage High C.P. Lamp.

Frosting the Bulbs.—In some cases the lower half of the bulb or *pip*, as it is termed, is frosted all round, and in other cases the whole bulb, either completely or in any special design. The effect is a much more subdued and evenly diffused light, giving a more pleasant effect to the eyes than a clear bulb; but, as will be seen later, the device absorbs a considerable proportion of the light. Frosting was originally done by dipping the glass bulb into a solution of so-called *white acid* prepared by slowly adding and mixing hydrofluoric acid with pure water and then adding small pieces of ammonium carbonate until all effervescence cease. The solution, now ready for dipping, must not be allowed to touch the naked skin, and, on account of its eating action on glass and most metals, must be mixed and contained in either copper or lead vessels. The lamp-bulb is of course removed from the solution when the action has gone on long enough to produce the desired degree of frosting. Other methods have been proposed for both permanently and temporarily frosting, but that used nowadays, and the one giving the best results, is by *sand-blast.* This consists in holding the lamp in the hand and continuously turning it about in front of a nozzle through which is forced a continuous stream of fine sand. The operator's arms pass through holes in the sides of a box having a glass front, and containing the jet. The sharp sand quickly scratches the bulb all over and imparts a frosted appearance to it. In this way any pattern can be marked, by letting the sand impinge through a covering over the lamp which is perforated with the pattern.

Coloured bulbs are largely used for theatre stage effects and illuminations, being either made from pure coloured glass or coloured by dipping the clear bulb in a suitable colour solution. This latter is prepared by dissolving aniline colour (*e.g.* blue, green, yellow, etc.) in ordinary collodion, thus forming a strongly adhesive dye which, while being unaffected by water, can be removed by alcohol, etc., if

required. The bulb, before being dipped in this dye, must be thoroughly cleansed from dirt and grease.

Efficiency of Incandescent Electric Lamps.—So far we have said very little about this extremely important subject, which must now be considered more in detail. The efficiency of an electric lamp, such as, for instance, that which we have up to the present been considering, is always spoken of, for commercial purposes, as the ratio of the total watts absorbed by the lamp to the total candle-power emitted: in other words, as so many *watts per candle.* This, however, is clearly the reciprocal of a ratio which invariably denotes the efficiency of all other energy-transforming devices. Consequently, since in all such instances we have

$$\text{Efficiency} = \frac{\text{useful energy developed}}{\text{total energy absorbed}},$$

the correct representation of the efficiency of a lamp should be in *candles per watt, i.e.* its *optical* efficiency as a light-emitting and energy-transforming device. In view, however, of the (at present) almost universal method of reckoning efficiency in watts per candle—an expression clearly meaning *in-efficiency*—we must reluctantly retain the expression. To make some distinction, we shall term the *watts per candle* the *commercial efficiency,* while the *candles per watt* we will call the *optical efficiency,* of a lamp.

Now the efficiency of an incandescent lamp varies with its candle-power, so that any mention of efficiency without stating the corresponding candle-power is meaningless. Unfortunately, too, there is no simple connection between these quantities, the candle-power increasing much more rapidly than the efficiency after the filament attains about one-fifth of its normal luminosity. The actual variation will be readily seen from a reference to the curves E and E_0 (Fig. 185) of commercial and optical efficiency respectively plotted from the results of a test on a well-known make of lamp marked '200.16.A.,' which, interpreted, signifies '200 volts, 16 c.p., class A.' This lamp was nearly new, and it will be seen that the candle-power begins to increase more rapidly than the efficiency after the filament attains a luminosity of about 2 c.p., being approximately 4·5 watts per candle at the normal c.p. This, however, is by no means the highest efficiency at which the lamp can be run, since by raising the voltage sufficiently almost any value of watts per candle, smaller than 4·5, can be obtained for a time.

The *life* of the filament under such conditions diminishes somewhat rapidly, and consequently there is a certain efficiency at which any

particular lamp may be run, with a given charge for electrical energy supplied to it, in order that it may have a reasonable life. Such we may term the *maximum economical efficiency*, and is that at which the cost of operating the lamp is a minimum. With the average cost of electrical energy in this country, no economy will be effected by using lamps of higher efficiency, or consuming a fewer number of watts per candle, than 3·5 in lamps of from 8 to 50 c.p.; for the increased cost of lamp renewals consequent on the much-diminished life at any higher

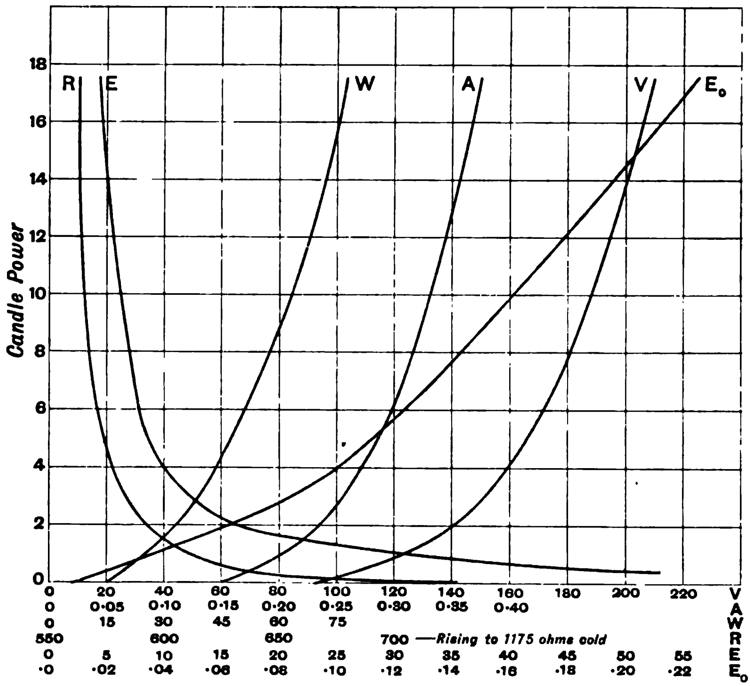


FIG. 185.—Photometric Curves of C.P. with Efficiency, etc.

efficiency will exceed the saving due to the smaller consumption of energy at the higher efficiency. The greater the number of watts per candle consumed, the longer the life and the more constant and uniform is the c.p. emitted. Although these glow-lamps are now made with definite efficiencies ranging from 2·0 to 5 watts per candle at normal c.p. and voltage, an efficiency of from 3·5 to 4·5 watts per candle is recommended by most lamp-makers, and should be employed, for reasons above stated.

Not only does the life of a glow-lamp greatly diminish with increase of efficiency, but also with increase of voltage, as is clearly

indicated in the following table of figures which are the means of the respective results obtained from a large number of Robertson lamps:—

TABLE XIII

Commercial Efficiency in Watts per Candle.	Average Life in Hours at							
	Normal Voltage.	Voltages above Normal.						
		1 %.	2 %.	3 %.	4 %.	5 %.	6 %.	7 %.
4·5	2200	1900	1700	1450	1300	1100	950	820
4·0	1550	1400	1150	950	850	750	660	600
3·5	1000	850	700	660	600	530	470	440
3·0	600	520	470	440	380	330	290	250
2·5	300	270	250	220	200	180	150	130
2·0	150	130	120	110	95	85	70	...

Reviewing these results in, say, the case of a 4·0 watts per candle lamp, we see that an increase of 25 per cent in efficiency diminishes the life by some 60 per cent at normal candle-power. Hence the variation of life is out of all reasonable proportion to that of efficiency.

Further, the higher the efficiency the more quickly is the lamp destroyed on a poorly regulated circuit. In Fig. 185 are given other curves marked R, W, A, and V, showing the variation of candle-power with filament resistance (R), with power absorbed in watts (W), with current through lamp in amperes (A), and with voltage (V) at its terminals respectively. These curves are interesting as showing how much more rapidly the candle-power increases than the resistance, watts, current, and voltage, after about one-eighth of the full luminosity has been obtained. Thus from the curve V between c.p. and voltage we see that an increase of about 2½ per cent in the voltage at or about its normal value raises the c.p. from 14 to 16, or some 14 per cent, *i.e.* a variation of 1 per cent in the voltage alters the c.p. by some 6 per cent at normal voltage, which is the case with glow-lamps in general.

By slightly increasing the voltage above normal we can therefore obtain some increase of efficiency and a large increase in the c.p. emitted. The effect of so doing, however, is well shown in Table XIII. in the diminution of life which results. On the other hand, the life increases enormously as the voltage diminishes from the normal value; but curves E and E_0 show what a disastrous effect this has on the efficiency.

Apparently, then, the consumer may on the one hand escape Scylla, and, on the other, fall in Charybdis if not careful. This leads us to what was mentioned on page 310, namely:—

Maximum Economic Efficiency.—This, as we have already remarked, is the efficiency at which the cost of operating the lamp is a minimum and at which the best all-round results are obtained, but is not the highest efficiency at which the lamp can be used. To be able to investigate this further in the case of any particular make of lamp, it is necessary to know the rate of variation of the life of the lamp with its commercial efficiency. Such a determination is usually lengthy, laborious, and expensive, entailing as it does life-tests on batches of the same type and make of lamp run at various efficiencies throughout. The results of such a test are given in Table XIII. for the Robertson lamp run at commercial efficiencies ranging between 2 and 4½ watts per candle. It should, however, be borne in mind that a similar test on another make of lamp might give very different results. Knowing, therefore, the following items:—

(1) Net cost of a new lamp to the consumer;

(2) Average life of the lamp when burnt at various efficiencies;

(3) Net cost of electrical energy delivered at the meter—the total cost of the lighting can easily be calculated.

If E is the commercial efficiency in watts per candle at which the lamp is used;

K, the candle-power of the lamp;

T, the time in hours for which it is used;

L, the life of the lamp in hours at the efficiency E;

P_e, the net price or cost in pence of electrical energy per B.O.T. unit to the consumer at the meter;

P_l, the net price or cost in pence of a new lamp to the consumer—

then the cost of lamp $= \frac{P_l \cdot T}{L}$ pence, and the cost of energy $= \frac{E \cdot K \cdot T \cdot P_e}{1000}$ pence.

If T be taken as one hour, then the above costs will be in pence per hour, which can at once be calculated. Taking a practical example, we will assume that for a Robertson high-voltage 16-c.p. lamp, $P_l = 17$ pence, and that L has the values given in Table XIII. at each efficiency. Let the cost of energy P_e be 5 pence, K being = 16 as above. Then on calculating each of the above costs for each value of E between 2 and 4·5 watts per candle, and plotting them in the form of curves, we obtain the curves A showing the relation between lamp cost and watts per candle, and D showing the relation between cost of energy and watts per candle, which latter is a straight line. Adding the ordinates (*e.g.* PQ and PR) of these curves together at different points along the

abscissæ (*e.g.* at P) we obtain a third curve F of *total cost* in pence of running the lamp for 1 hour. The lowest point M of this curve gives the minimum total cost per hour, and the commercial efficiency (2·5 watts per candle) corresponding to this point M is therefore the

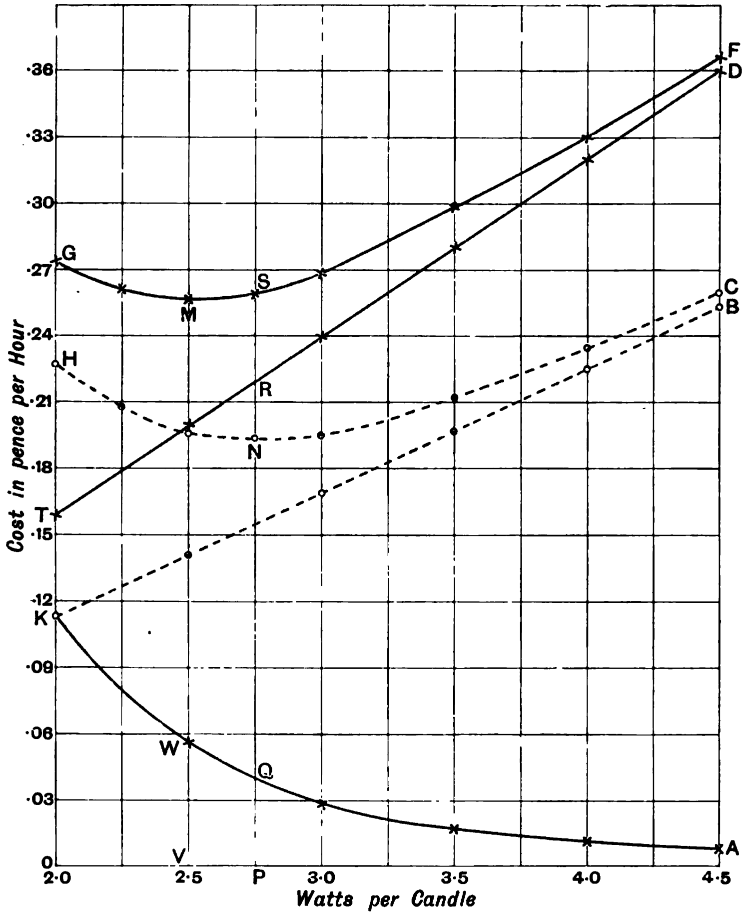


FIG. 186.—Curves showing Maximum Economic Efficiency.

efficiency at which the total cost of operating this lamp is a minimum, or the *maximum economic efficiency.*

If P_e is taken as $3\frac{1}{2}$d. per B.O.T. unit, the cost of lamps and other items remaining the same, then curve A will be as before and B will be the new 'cost-of-energy' curve. The curve of *total cost* is now indicated at C, the minimum value of which is N. Hence the corresponding maximum economic efficiency is 2·75 watts per candle.

In this way it can be shown that as the cost of energy diminishes the portion of the total-cost curve to the left of the minimum point becomes steeper, while that to the right becomes more nearly horizontal, and hence very flat. Thus when energy is very cheap a considerable variation of efficiency makes very little difference in the total cost of operation, therefore the lamp may be operated at a larger number of watts per candle, and its life thereby prolonged considerably.

The foregoing deductions are so important to the consumer that they may be otherwise stated as follows:—

With energy at 5d. per unit, the ordinates of the curves D and A show that the cost of energy is a much heavier item than the cost of lamps. Consequently the consumer will gain by economising in electrical energy at the expense of a greater number of lamp renewals. This is effected by using high efficiency lamps of the same c.p. (taking in this case 2·5 watts per candle).

Again, with reference to curves A, B, and C, the ratio $\frac{PQ}{PN} = 0{\cdot}21$ nearly, and for curves A, D, and F we have $\frac{VW}{VM} = 0{\cdot}21$ approximately. These figures show us that for an installation using the lamps in question the total cost will be a minimum when the cost of lamps is about 21 per cent of the total cost. This means that if the lamp bills are less than 21 per cent of the total cost, higher efficiency lamps having a shorter life should be used so as to bring the lamp bill up to 21 per cent. The opposite is of course equally true, but it must not be forgotten that the above reasoning might not necessarily hold good when the maximum economic efficiency of a complete electric light plant (including engines, dynamos, etc.) is considered.

It may here be remarked, as a set-off to the preceding considerations, that the Robertson Lamp Company recommends an efficiency of 4 watts per candle (w.p.c.) for 16-c.p. high-voltage lamps, and 4·5 w.p.c. for lamps of 8 c.p. and less. The Sunbeam Lamp Company fix their standard efficiency at 3·75 w.p.c. for c.p.'s between 16 and 32, and 4 w.p.c. for 8-c.p. lamps.

Life of a Glow-Lamp.—This, as we have seen, depends on the efficiency at which it is worked, *i.e.* on the temperature or degree of incandescence to which the filament is run.

P. Janet[1] has determined by electrical measurements the temperature of several 10-c.p. lamps taking 0·65 ampere. From his results it would seem that the temperature at normal c.p. is about 1620°.

Mr. Carl Hering and subsequently Mr. Weaver have discussed in

[1] *Comptes rendus*, 126. pp. 734-736 (1898).

some detail the most economical life as well as the total life of a lamp. The relations deducible from such considerations are purely empirical, and depend on the increase in the watts per candle per hour, which varies with each make of lamp. Professor Thomas found that the efficiency varied at a rate corresponding to an increment of 0·003 watt per candle per hour for lamps up to about 100 volts, and was very fairly uniform. This increase in the watts per candle per hour would, however, be greater in the case of a 200-volt lamp.

If several lamps of the same type and make are run at different voltages V, it is found that the average life is proportional to $\frac{1}{V^{25}}$, *i.e.* to V^{-25}, while the optical efficiency E_0 is proportional to V^4 and amounts to only about 6 per cent or 7 per cent for the type of lamp so far considered. This efficiency, though small, is somewhat higher than that of an ordinary gas-burner. If C is the current through the lamp, it is found that the candle-power is proportional to C^5 or V^6; whence the life will be proportional to $\frac{1}{E_0^{6\cdot25}}$ and to $\frac{1}{(CP)^{4\cdot25}}$, where CP is the candle-power. It must be clearly understood that these relations are only approximate, and will vary somewhat in different lamps.

F. W. C. Bailey,[1] in an exhaustive series of tests on 220-volt 16-c.p. lamps of different forms and makes, finds that the useful life of the lamps is from 450 to 500 hours, which is about the same as a 3-w.p.c. 100-volt life. On the other hand, G. V. Williams, in a paper read in June 1901, an abridgment of which is given in the same journal of August 10, 1901, gives results of tests made by several supply companies, with life curves, and states that several batches of 220-volt lamps had an average life of 750 to 930 hours without losing more than 20 per cent of their rated c.p., and taking 4·18 to 4·6 watts per candle.

Uniformity of Filaments.—Although the object of flashing a filament is to obtain a uniform cross section, this is seldom obtained, the mean diameter of the filament close to the platinum mounts often being from 25 to 50 per cent less than at the bottom of the loop. This is easily explained by the fact that, in flashing, the hottest parts obtain the greatest deposition of carbon. Now the temperature of the filament near the mounts is less than at the loop owing to the conduction of heat along the platinum wires, consequently less carbon is deposited here.

Causes of Failure.—The two main causes of failure in ordinary glow-lamps may be owing to—

(1) A badly flashed filament or one of non-uniform section, the

[1] *West. Electn.* 30. p. 425; Discussion, pp. 425, 426, June 14, 1902.

thin parts becoming rapidly thinner, due to volatilisation caused by reason of their higher temperature;

(2) Poor vacuum, causing the filament to rapidly disintegrate, and which can be detected by the impossibility of keeping the hand on the bulb when the lamp is in use owing to it being so hot.

To these may be added others, namely:—

(3) Air leaking into the bulb at the platinum leading-in wires;

(4) Excess voltage, causing the filament to glow to dazzling whiteness and rapidly disintegrate;

(5) Bad joint between filament and leading-in wires;

(6) Loose caps.

It is folly and mistaken economy to use cheap lamps of poor quality. The quality of a lamp can best be gauged by seeing the *candle-hours* given out before the c.p. falls to 80 per cent of its initial value, at which stage many central-station engineers consider the lamp to have reached the end of its *useful life*, and that it should be replaced by a new one. If an average useful life of 600 hours is assumed, then an inferior lamp often gives only 60 per cent or 70 per cent of the candle-hours of a good lamp. The small difference in first cost between a good and an inferior lamp is quite insignificant compared with the corresponding difference in the cost of the useful candle-hours in the two cases. From this it follows that the proper renewal of lamps with time of use is a matter of the greatest importance to consumers from the point of view of economy.

The blackening of the bulb is supposed to be due to the deposition of carbon on its inside, the filament slowly volatilising at the high temperature and the vapour becoming deposited on the colder surface of the glass. Some authorities, however, assert that the blackening is largely a chemical effect, and is responsible for very little of the drop in c.p., most of it being due to the alteration in the area of the filament surface. Further, that the deposit does not depend on the degree of exhaustion. Cheap lamps exhibit this effect, however, in a marked degree, owing, it would seem, to the usually poor vacuum obtained and probably imperfect flashing, the result being a diminishing efficiency and light, owing to absorption of light by the blackened bulb coupled with a smaller current and therefore filament-temperature caused by a thinning of the filament. W. M. Stine states that the loss of c.p. is due to the repeated heating of the filament annealing the outer layer of carbon obtained by flashing, thus making it more amorphous with greater emissivity and lower temperature.

The effect of 'fire-damp' in fiery mines on glow-lamp filaments

has been investigated by H. Couriot and J. Mennier,[1] who introduced a mixture of fire-damp and air (9·5 per cent of methane) into the bulbs of from 15- to 110-volt lamps taking various currents up to 2·15 amperes. With none of the lamps in which the filaments were not previously broken was there an explosion with the most explosive mixture, though the filaments all burnt out. The authors, however, managed to explode a mixture by a succession of the sparks caused by the ends of a broken filament coming together when shaken, but in no case by any incandescent metal or carbon wire. This is an important matter for mining engineers, as proving the safety attending the use of glow-lamps in any mine.

Silicon Carbide Lamp.—This lamp, invented by Langhans, was introduced by the Premier Electric Lamp Syndicate. It differs from the ordinary carbon-filament lamp in the treatment and composition of the filament. Silicon in the form of a fine amorphous powder is mixed with the cellulose, which has been treated with either sulphuric acid or this and phosphoric acid together. The filament is then formed in the usual way and carbonised by being surrounded in a muffle with powdered carbon and titanic acid to protect the silicon from any traces of nitrogen that may be present. The temperature is raised high enough to cause the carbon and silicon to combine, and the filaments are finally flashed in a vapour containing these two non-metals. It is claimed that, owing to the high refractory nature of these filaments, they can be run at a higher temperature, and therefore a higher efficiency, than can ordinary carbon filaments, and this without blackening of the bulb, etc.

The Crawford-Voelker incandescent lamp has a filament of titanium carbide and is bifurcated, the two ends of the filament being separated by glass which prevents any discharge at the higher pressures.

Siemens and Halske have devised a method of making filaments of tubes, drawn or rolled out of tantalum or niobium, which can be filled with conducting substance. This firm have also used a mixture of thorium with thorium carbide for filaments, filaments of thorium alone being mechanically weak.

Osmium Lamp.—This is an incandescent lamp of modern origin having some valuable properties, and is the invention of Dr. Aner von Welsbach. It differs from the ordinary carbon-filament lamp in the composition of the filament, which, however, is also enclosed in a vacuum. The filaments are made by mixing finely divided osmium with soot and adding a solution of cane-sugar, grape-sugar, and gum-

[1] *Comptes rendus*, 127. pp. 559-561 (1898).

arabic to form a paste, which is then forced through diamond dies. Metal and glass dies cannot be used owing to a harmful effect on the filament. The filaments being of somewhat low resistance, it is difficult to make the osmium lamp for high voltages owing to the length of filament required for such. The filament, which is very hard and brittle and of dull greyish colour, tends to warp, but it has been found possible to make lamps of 2·5 c.p. at 4 volts. They are made for pressures up to 75 volts, a 32-c.p. lamp being the smallest size at this voltage. This size has a filament about 40 cms. long and 0·1 mm. diameter, with a specific resistance at bright yellow heat of 10^5 C.G.S. units, and takes only 1·5 watt per c.p. Fig. 187 shows an osmium lamp as supplied by the General Electric Company of London. As seen, the filament consists of three loops in series with one another, and each anchored at its lower end.

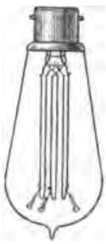


FIG. 187.—Osmium Lamp.

In recent tests the c.p. of a 1·5-w.p.c. lamp was found to diminish some 9 per cent after 1000 hours, while the life was over 2000 hours. Wedding found the average life of eighteen lamps which he tested to be 1900 hours, though some ran for over 4000 hours. The lamps on the average took 2·1 w.p.c. with a loss of 20 per cent in c.p. to the end of the test. In another test a 30-c.p. 37-volt osmium lamp taking 1·46 w.p.c. gave 24·2 c.p. after 1299 hours and took 1·76 w.p.c., and after 3132 hours gave 23·7 c.p. taking 1·78 w.p.c., the current being 1·19 ampere at starting and 1·13 at the end of 3132 hours.

One important feature of the osmium lamp is that it is capable of withstanding an increase of voltage of from 50 per cent to 70 per cent without burning out, whilst the ordinary carbon-filament lamp could not stand a 10 per cent increase over the voltage for which it was made for an equal time. The colour of the light in the osmium and carbon-filament lamps is much about the same, while the relation between c.p. with amperes, volts, watts, and efficiency respectively, as shown in Fig. 185, is also similar. The filament resistance, however, of the osmium lamp *increases*, whilst that of the ordinary carbon lamp *decreases*, for increase of current.

An interesting point is raised in connection with the temperature of the filament. H. F. Weber, in 1891, showed that the absolute temperature of the carbon filament under ordinary conditions lay between 1565° and 1620°, and from $\frac{1}{10}$ to $1\frac{1}{2}$ times normal brightness the change of temperature amounts to something like 180° only. Now in the osmium lamp, according to Lombardi, the absolute temperature is,

under normal conditions, about 1435°; and therefore it would appear that the osmium lamp with a lower temperature has a higher efficiency than the ordinary carbon-filament lamp with a higher temperature. Comparing this with the statement on page 297, it would seem difficult to balance the two, and more than one reason has been suggested to account for it.

The absolute temperature T is deducible from the relation

$$T\epsilon^{KT} = \frac{C.V}{J} \cdot \frac{1}{K_r S},$$

where K_r is the radiation constant, which Lombardi finds to be 0·0000164 for osmium lamps, and Weber finds to be 0·0000171 for black carbon and 0·0000129 for grey or graphitic carbon. J represents Joule's equivalent, S the radiating surface of the filament, C the current, V the volts, K a constant for all solid bodies having the value 0·0043, ϵ the Napierian logarithmic base = 2·71828.

An interesting paper, comparing the optical efficiencies of different forms of lamps together with the colour and spectra of the light, is given by W. Vöge (*vide* footnote, p. 295).

'Osmi' lamps, as they are now briefly termed commercially, are run three in series for low-voltage and five in series for high-voltage circuits, each batch comprising lamps of the same voltage and c.p.

Evacuation: Air-Pumps.—We may now turn our attention to the ways and means for producing a vacuum in electric incandescent lamps. While this vacuum should be as good as possible in order that the loss of heat by conduction and convection from the filament to the bulb may be minimised, the vacuum obtained in such lamps is far from being a *perfect* one. Improvements in air-pumps, by means of which a vacuum is obtained, coupled with various expedients resorted to in their application, have resulted in much better vacua being obtained more expeditiously now than some few years ago. The many forms[1] of air-pumps may be broadly classified as follows: (1) Mechanical pumps, non-mercurial; (2) Mercurial pumps, non-mechanical; (3) Mechanical-mercurial pumps.

Of the purely mechanical types of air-pump, in which no mercury is employed, it will suffice to take the now well-known *Fleuss* '**Geryk**' *vacuum-pump* made by the Pulsometer Engineering Company, of

[1] Double-acting mercury pump (*Zeitschr. Instrumentenk.* 23, pp. 47-49, Feb. 1903); automatic mercury-jet air-pump (*Ann. d. Physik*, 10. 3, pp. 623-646, Feb. 1903); mercury rotary air-pump for vacuums of $\frac{1}{570000}$ atmosphere (*N. Cimento*, 5. pp. 233-242, April 1903); automatic mercury vacuum-pump, Toepler type (*Phil. Mag.* 6. pp. 316-322, Sept. 1903); mercury vacuum-pump (*N. Cimento*, 1. pp. 187-189, March 1901).

Reading, and which has a reciprocating motion. Mechanical pumps prior to the introduction of the Geryk form some eleven years ago could not be depended upon for producing a vacuum of less than 2·5 millimetres off perfect. This degree of vacuum was of course useless for electric incandescent lamps, and therefore such a pump was only used in the manufacture in conjunction with a more efficient pump (p. 324).

The general appearance of a *Geryk air-pump* of the so-called *duplex* form, which is one very common form of this pump, is illustrated in Fig. 188. The principle on which it works, together with the construction,

FIG. 188.—Duplex Geryk Air-Pump.

will be understood from a reference to Fig. 189, which is a sectional elevation of one of the cylinders—the right-hand one, the other being, however, precisely similar, except that it has no pipe at the top end. As seen, each complete cylinder is made up of two halves, provided with flanges, which are bolted together with air-tight packing between them. A central piston-rod passes or works through a stuffing-box at the top of the cylinder, and carries a piston of peculiar form at the lower end. This piston consists of a cup-shaped casting screwed on to the lower end of the piston-rod and carrying another small flanged casting which is partially enclosed by the cup and which contains a valve E. Between the rim of the cup- and flange-shaped piston castings is

clamped a leather bucket C, which is an easy fit in the cylinder and is kept up to the walls of the cylinder by the pressure of the oil J in the annular space D. The suction-pipe A, leading to the receptacle to be exhausted, communicates with the cylinder above the piston through an air-port B.

An air-pipe F communicates from A and B to the under side of the piston, and is for the purpose of relieving the piston on the first few strokes. The piston-rod works *freely* through both a combined stuffing-box I and delivery-valve collar G situated at the region of the joint between the two halves of the cylinder. It will be noticed that an air-tight joint between the stuffing-box and piston is made by means of an hydraulic collar I, the flange or face of which is pressed down on its seating by a spring K, and so covers and makes an air-tight joint between the valve-collar G and annular casting H. The arrangement thus forms a frictionless equivalent of a stuffing-box and delivery-valve combined. A special oil, having a very small vapour tension, is contained in the upper half of the cylinder over GI up to the overflow level of the oil-filling plug L. Similar oil J covers the piston (at its lowest point of travel) to just under the level of the port B.

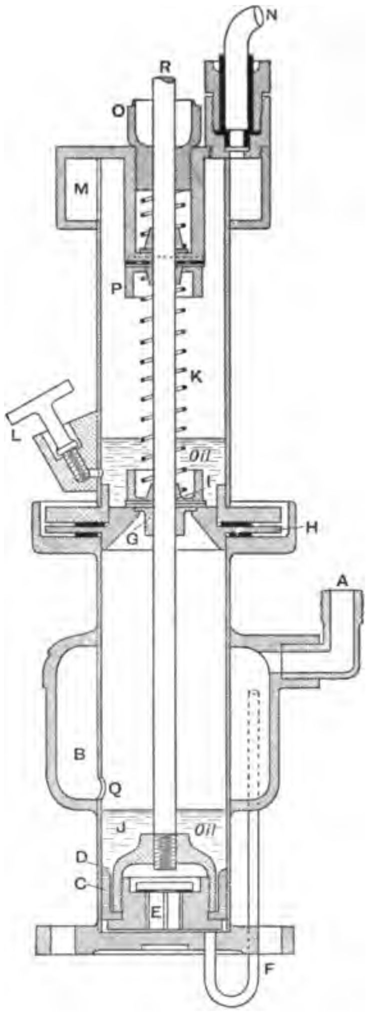


FIG. 189.—Section of Geryk Air-Pump.

The Action of the pump will now be easily understood, and is as follows:—When the piston is at the bottom of a stroke there is a perfectly free opening from A to B. As the piston rises the port B is cut off and the cylinder full of air is irresistibly carried up to the outlet valve G. No air can by any possibility get back past the piston, as the piston is covered more than half an inch deep with oil. As the

piston continues to rise and the pressure upon it increases, so the leather bucket C is forced more tightly against the walls of the cylinder. Whatever oil gets below the piston is immediately picked up through the valve E when the piston gets to the bottom of its stroke again. The piston-valve E only moves when the pump begins to exhaust, and is quite inactive when the vacuum reaches about 13 mm. less than perfect. When the piston is at the top of its stroke it is in contact with the valve G and lifts G $\frac{1}{4}$ in. off its face, giving a free outlet for the air But there is so much oil on the piston that a considerable quantity of it is forced through the valve at G, driving all air before it. While the piston is at the top of its stroke the valve cannot close, and the oil at J and in K becomes, for the time being, all one body, so that no air can possibly return although the valve is fully open. As the valve G is resting on the piston it cannot close until the piston has made $\frac{1}{4}$ in. of its descent, and consequently oil equal to $\frac{1}{4}$ in. in depth will have entered the cylinder ready to be discharged behind the air upon the next up-stroke.

From the above description it will be seen that all working joints are liquid-sealed and self-adjusting, and therefore the vacuum is independent of tight-fitting mechanical pistons and of wear. Also all valves are automatic, so that the air meets with no resistance at all. There is no clearance space, and both the suction and delivery of air is absolute, however slowly the pump is worked.

With a single-cylinder pump a vacuum within $\frac{1}{4}$ of a millimetre can readily be obtained. With a double- or duplex-cylinder pump, such as that shown in Fig. 188 with the two cylinders in series, *i.e.* with the second barrel exhausting from the first, a very much higher vacuum can be produced. With a good drying-tube a vacuum within $\frac{1}{5000}$ part of a millimetre less than perfect (measured on a large M'Leod gauge) has been obtained with such a pump.

The Geryk vacuum-pump is largely used by incandescent electric-lamp makers both for '*roughing out*' preliminary to final exhaustion by means of the next pump to be described, and also for final exhaustion. The size of pump usually employed by them is that listed as Duplex B and shown in Fig. 188. The diameters of the cylinders of this pump are each $2\frac{1}{2}$ ins. and the stroke of the piston 5 ins. The time taken to get a vacuum depends on the size of the vessel to be exhausted and the degree of exhaustion required; but the above pump will exhaust about as much in one minute as a Sprengel mercury pump (p. 324) will in an hour, while giving a vacuum comparable with that of the Sprengel. It has the further advantages of requiring very little power to work it owing to friction being reduced to a minimum,

and of being able to hold a vacuum for any length of time. The speed of the fly-wheel should be from 35 to 40 revolutions per minute. A drying-bulb containing phosphoric anhydride must always be inserted as close to the pump as possible, and between it and the vessel to be evacuated, for it is as important to keep the pump-oil free from water vapour as the vessel to be exhausted (*vide* p. 327).

The Geryk pump is also made in sizes up to a capacity of 100 cubic feet per minute; which size, having two 15-in. and two 9-in. cylinders, requires only 2 h.p. to drive it. The Duplex pump worked with the two cylinders in parallel, *i.e.* both exhausting from the vessel, a vacuum to within 0·25 mm. can be obtained. When worked with the two cylinders in series, *i.e.* one exhausting from the vessel to be evacuated and the other cylinder exhausting from the first, a vacuum something like $\frac{1}{5000}$ mm. less than perfect can be obtained with clean dry air. Cylinders in parallel exhaust twice as much air in a given time as when in series.

Turning now to the second class of pump, it should be remembered that while several kinds of non-mechanical mercurial air-pumps have been devised from time to time, that known as the *Sprengel* is the most widely used. The form or general arrangement of this air-pump varies slightly, however, with the firm employing it, but the form as used at the present time by one of the largest lamp manufacturers in this country is shown diagrammatically in Fig. 190. It consists of a connected system of glass tubes, bulbs, and cisterns combined with some convenient form of quick-acting mechanical air-pump which is in communication with tube P direct and with C through an additional valve not shown. Some five or six glow-lamps, only one (L) of which is shown, are simultaneously exhausted, being fused to the glass nipples N of a cross-tube H, which is in communication with the pump-head M through a drying-tube T containing some highly hygroscopic substance such as phosphoric anhydride (as a drying agent). The pump-head M comprises an outer tube through one end of which is fused an inner tube G provided with five or six jets pointing downwards. To the outer tube, and opposite each jet, is fused a *fall-tube* F about 8 ins. long, the lower ends of which are fused into a cross-tube Q leading to the reservoir D. This communicates with P and another reservoir E through a non-return valve V in the form of a float-tap which allows mercury to descend but not to flow upwards. A bulb K is in communication with P, the pump-head M through an air-trap A, and a larger reservoir E through a pipe B about 32 ins. long.

The action of the pump and operation of exhausting is as follows: The mechanical pump first exhausts to the limit of its ability,

depending on the type of pump used (up to 28 ins. of mercury for the ordinary plunger form; much more in the case of an oil-sealed Fleuss pump, which is always the type used). The upper portions of the

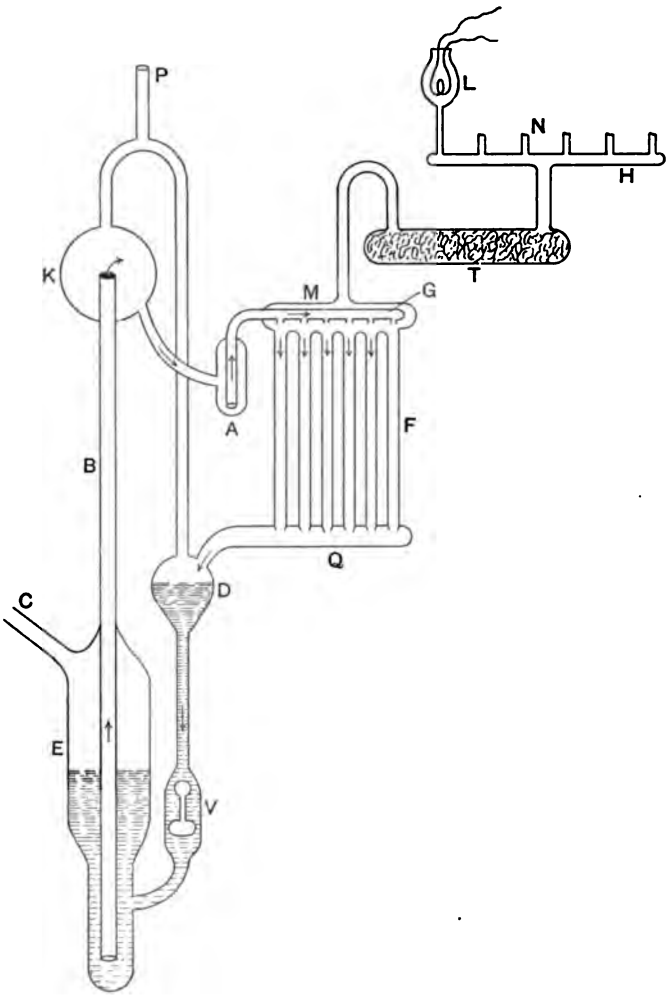


FIG. 190.—Principle of Sprengel Air-Pump.

system, including lamps L, are exhausted through P and the reservoir E, above the mercury in it, and through the valve not shown, this operation being commonly known as *roughing out.* Mercury now flows by gravity out of D into E through valve V. Air is next automatically admitted to E, the mercury in which is then forced up the pipe B into K, when it falls by gravity to M, and through the jets

in G into the fall-tubes F, and thence into the tube Q and reservoir D again.

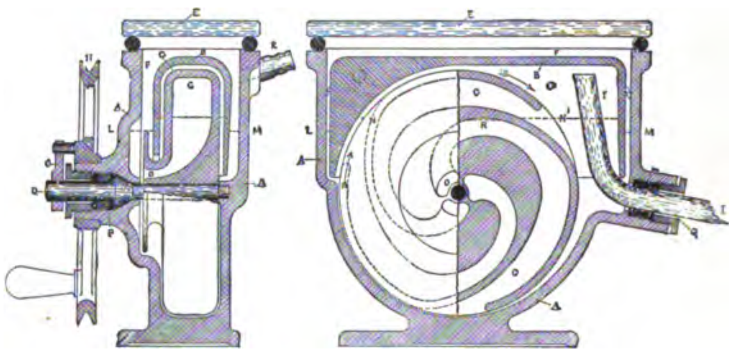
The mercury has thus completed a cycle of motion in the path of the arrows, but it flows through each jet in G in a stream which is more or less discontinuous. Each element of the stream may be regarded as a little piston which takes with it, and pushes before it down the tubes F, a globule of the air still remaining in the bulbs L. These globules collect in D and are taken away at P in a continuous manner by the mechanical pump, which is kept running all the time. The residual air in L is thus extracted little by little. If C is now connected to the mechanical pump for a few moments, E is exhausted, and mercury flows out of D into E again, to be once more forced into K on admitting air at C. The mercury thus raised to K again falls through A, M, F, and Q into D, to be used over and over again. The residue of the air in the bulbs L which the mechanical pump could not remove is thus rapidly extracted, and at the final stage the bulbs L are gently heated by gas jets to vaporise the moist air clinging to the inner surface of the bulbs, and which is the chief enemy to a complete or perfect exhaustion. The filament is also made to glow to somewhat over normal brightness to get rid of occluded gas in the filament and wires, etc. The drying-tube T is necessary for drying the air as much as possible in the bulbs L and that passing to M. Any particles of air which might pass from K towards M are trapped in the upper part of A.

The time taken to exhaust the bulbs L from first starting the pump to sealing the bulbs off from the nipples N is about twenty minutes when a Fleuss 'Geryk' pump is used for roughing out, and the vacuum obtained is almost absolute in the case of such a pump as the above. As the degree of exhaustion goes on, the noise of the pellets or drops of mercury striking one another in the fall-tubes F increases. When the noise or clicking of these ceases to increase, the vacuum is known to be sufficiently good and the lamps are sealed off one at a time.

The arrangement of pump shown has the advantage that the operator is secured against the poisonous vapour given off by mercury exposed to the air; for, as seen, all the mercury is completely enclosed. This is very important, seeing that in most of the large lamp factories several tons of mercury are in circulation through the many pumps employed. The means employed by different manufacturers for producing the circulation of mercury—in other words, for raising the mercury from the bottom reservoir, such as E, to the top reservoir, as for instance K—vary somewhat.

The only important example of air-pump coming under the last-named class given on page 319 is that devised and put on the market recently by Professors Barr and Stroud of Glasgow. This mechanical vacuum-pump is purely of a rotatory type and contains mercury, which features distinguish it clearly from the Geryk mechanical vacuum-pump.

The construction and action of the Barr and Stroud air-pump is simple and in many ways novel, and will be understood from a reference to the sectional end and side elevational drawings of one of these pumps as shown in Fig. 191 (I. and II.). It consists of a somewhat flat-shaped cast-iron box or receptacle A, the lower half of



I. II.

FIG. 191.—Barr and Stroud Rotary Air-Pump.

the ends of which is nearly semicircular and is provided with a foot. Through a hollow boss of rather special design about the centre of one side passes a shaft Q which terminates in a boring in the opposite side that does not go through to the outside as seen in Fig. 191 (I.). Against the base of the coned collar seen on this shaft is pressed suitable packing P by means of a flanged nut. The shaft is rotated by turning the V-grooved pulley H either by hand or by a round belt from a small motor. This pulley rotates on the outside of the hollow boss and drives the shaft by means of a pin in its side engaging the arm C fixed to the shaft. Mounted on the shaft inside the box, and driven by it, is a rather wide circular disc G, which is flat on one side and terminates on the other in a peculiar-shaped boss having an annular recess in its periphery, as seen in Fig. 191 (I.). Over the upper portion of this rotating drum and enveloping both sides and periphery is a cast-iron box B. The outer box A has an air-tight cover formed by a thick glass plate E with rubber packing, indicated

by the black circles, between it and the rim of the outer box A. The rotating drum has three separate spiral channels leading from its periphery to the face of the boss, as shown at O, Fig. 191 (I. and II.). A pipe or tube I, Fig. 191 (II.), passes through an air-tight stuffing-box or gland Q in the outer case A into the inside of the box-cover B, thus communicating from the vessel to be exhausted to the inside of B. The rapidity of exhaustion is increased by connecting the space F outside B and between B and A with an ordinary mechanical air-pump through the pipe R, which communicates with the space F. Mercury is poured into the pump and takes the level LM between A and B and the level NN^1 between G and B.

The Action of the pump is as follows: The handle being slowly turned so as to slowly rotate the drum in the direction of the arrow, the portion of each channel O as it rises above the surface of the mercury NN^1 is filled with the air inside B. This volume of air is forced through the channel as its mouth turns below the line NN^1, and the mercury forces its way in like a very tight-fitting piston. This air finds an outlet through the apertures in the boss of the drum into the space F outside B, and is then taken out of this by the roughing-out pump attached to R.

The pump, though rotated very slowly, is fairly quick-acting; for, since there are three channels O, three gulps of air are taken from the inside of B, and therefore from the vessel being evacuated, per revolution. Very little power is needed to drive the pump, which is very suitable for exhausting electric lamp bulbs. Far higher vacua can be obtained with this type of pump (by letting it work longer on the exhaustion) than is required for an electric glow-lamp. The time taken to exhaust will, as in the previous pump considered, depend on the size of vessel to be exhausted, the degree of vacuum required, and the care with which the air is dried. A drying-tube of phosphoric acid must be placed between the pump and its work, and, of course, close to the pump in the pipe I; and the vessel to be exhausted should be close to the pump.

A vessel which has been once evacuated can be exhausted again soon after in far less time, due to the aqueous vapour usually clinging to the surface of the vessel having been got rid of.

The chief feature of the Berrenberg lamp is that the vacuum is produced by a mechanical pump in which all joints, valves, etc., are enclosed in a vacuum-jacket, which is maintained by a second pump producing a rough vacuum. It is claimed that the absence of mercury vapour in the lamp prevents the blackening of the bulb with use.

Liquid-Air Evacuation.—A description of the ways and means for obtaining a vacuum would hardly be complete without the mention of a very simple and rapid method by means of liquid air. This simple, though extremely important, substance, destined, no doubt, to play an important part in commercial undertakings in the future, was first discovered or obtained by Professor Dewar. A brief allusion to the way in which liquid air is now obtained may not be out of place here.

Air at from 180 to 200 atmospheres pressure is allowed to escape into a copper tube through a small nozzle near the end, being cooled on expansion. This cooled air flows out at the other open end, and is led back along the outside of this first tube to an expansion-valve. The air, following on through the first nozzle, is thus cooled before expanding, and falls to a still lower temperature on expanding. After this action has continued from five to ten minutes, the temperature is found to have fallen to below $-120°$ C., and the air escaping at the expansion-valve is liquefied and can be collected at the rate of over 1 litre (1000 c.c.) per hour.

Beyond the foregoing brief indication of the way in which liquid air is obtained, space will not permit of a description of the various kinds of apparatus[1] employed in its production. The density of freshly made liquid air, as determined by Knipp,[2] is 0·933, which increases to a steady density equal to that of liquid oxygen; while the surface tension of fresh liquid is between 9 and 10 dynes per cm., rising to a final value of about 13·4 after several hours. (The surface tension of water at 18° C. equals about 73·3 dynes per cm.)

Returning now to the method of evacuation by means of liquid air, all that is necessary is to place the vessel A to be exhausted in communication with another vessel B whose bulb is immersed in a third receptacle C containing the liquid air, when it will be almost instantaneously exhausted of all air. This is due to the extremely low temperature ($-120°$ C. or less) of the liquid air in C causing the air in A to condense in B, thus leaving a vacuum in A as desired. Notwithstanding the vacuum-jacket with which C would have to be surrounded to prevent convection, the liquid air in it would gradually diminish in volume. Whether or not such a method would be economical enough for commercial use on any large scale, would depend on the cost of production of the liquid air.

Evacuation by Absorption Chemically.—Yet another method of

[1] *Acad. Sci. Cracovie*, Bull. 10, pp. 619-633, Dec. 1902; *Canad. Elect. News*, 12. pp. 191-192, Nov. 1902; *Phys. Rev.* 15. pp. 181-187, Sept. 1902.

[2] *Phys. Rev.* 14. pp. 75-82, Feb. 1902.

producing a vacuum is that used in the Malignani process,[1] in which the vacuum is obtained in the bulb by the absorption of the gases by certain chemicals. Red phosphorus, which is generally used, is introduced, with hydrocarbon gases, into the bulb, which is evacuated by a mechanical roughing-out air-pump. The filament is made to glow, and the bulb finally heated on the outside; then, when the electric-glow discharge disappears, the vacuum is complete, and the lamp sealed off. The advantages claimed are that the vacuum is more perfect and more rapidly obtained than with the ordinary pump method, and this without using a *mercury* pump. Another chemical process of exhausting is described by S. E. Doane (*Elect. World and Engineer*, 43. pp. 963-965, May 21, 1904).

Degree of Exhaustion: Vacuum Gauge.—It has been mentioned that the vacuum obtained with the above pump is almost *absolute*, the Sprengel type of mercury-pump being extremely efficient. Some lamp manufacturers employ a pressure-gauge to indicate the degree of exhaustion; others estimate the vacuum by well-known signs accompanying the process. The latter method is naturally a rough and ready one, and can give only a rough idea of the degree of exhaustion, which may be sufficient for some purposes. There is no difficulty in comparing accurately the degree of exhaustion in different vacua, but there is a difficulty in making a rational quantitative determination of the degree of exhaustion of any particular vacuum. Naturally such has reference to some arbitrary standard which is taken to be the standard pressure of the atmosphere, namely, that due to the weight of a column of mercury 760 mm. high. The M'Leod vacuum-gauge is always used for comparing or determining vacua. The principle involved consists in compressing a large known volume of the rarefied air of the vacuum to be tested into a comparatively small, but known, volume. The pressure of the compressed air is then compared with that of the vacuum.

Measurement of the Degree of Vacuum.—One of the best devices for effecting this is the M'Leod pressure- or vacuum-gauge, the principle of which is shown in Fig. 192. It consists of a system of glass tubes and bulbs TF and DNA in two parts. The joint at B between them is usually a well-ground one having a cup containing mercury as a seal. This joint is merely for convenience in manufacture, as it would be difficult to handle so lengthy a system of glass tubes in one piece; the height between levels T and D being about 3 feet, and between levels D and N also about 3 feet. The end A of the side tube is connected to the pump or vessel to be exhausted,

[1] *Sci. Amer.* 83. p. 213, Oct. 6, 1900.

with an efficient drying-tube between A and the pump or vessel. A glass reservoir H of mercury is in connection with the lower end of BT through a flexible tube RT having a pinch-cock at K, which can be regulated by a screw. This reservoir H can be raised or lowered by means of a cord S passing over a pulley-block P. The stem EF is of small-bore capillary tube, and its volume above the mark E is carefully measured by the weight of mercury required to fill it, as also is the volume between levels D and GE. These relative volumes are noted for future reference. The stem GN is also graduated, G being on the same level as E. The capacity of the vessel VC between levels D and E might conveniently be 100 c.c., and that of EF $\frac{1}{10}$ c.c.

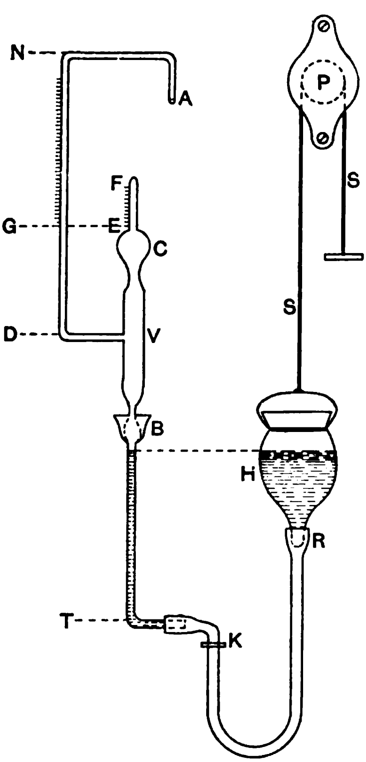


FIG. 192.—Principle of M'Leod Vacuum-Gauge.

The operation of testing a vacuum is as follows: The reservoir H is lowered until the level of the mercury in it, and therefore in TV, is below that of D. The pump being in action, the system above the column of mercury in VT is exhausted to the same degree as the vessel being evacuated. H is now raised, and mercury flows by gravity up DGN and VF, thus displacing and compressing in a known smaller volume the residual air in VF which the pump had failed to remove. The corresponding increase of pressure of this small volume becomes measurable by a rise of the mercury in GN. As an example, if the admission of mercury to the vessel compresses the residual air to $\frac{1}{100}$ of its original volume, it will have increased its pressure to 100 atmospheres—*i.e.*, of course, 100 atmospheres of the vacuum to be measured. Now, supposing that under these conditions the mercury in GN had risen 100 mm., it is obvious that the residual air in the vessel before any mercury was admitted was at a tension of 1 mm. Clearly, if a perfect vacuum existed, the mercury would rise to the *same level* in both EF and GN; and again, if the relative capacities of

VC and EF were as 1000 : 1, and the mercury stood at E and 1 mm. above G, then the air in VC will have been compressed to $\frac{1}{1000}$ of its original volume and its pressure increased to 1000 atmospheres of vacuum. Hence the residual air in VCF before admission of mercury was at a tension of $1 \times \frac{1}{1000}$, or $\frac{1}{1000}$ of a mm., and the vacuum is said to be $\frac{1}{1000}$ mm. less than perfect. Other pressure-gauges[1] or manometers have been devised which cannot be considered here.

Nernst Incandescent Electric Lamp.—This differs in several ways from the ordinary carbon-filament glow-lamp considered in the preceding pages. The Nernst filament is not enclosed in a vacuum; and further, instead of being carbon, it is made of some highly refractory oxides (or so-called 'rare earths'), such as those of zirconia, thoria, or yttria, worked up into the form of little rods and mounted on two platinum wires by means of a paste of refractory oxides. At the outset Professor Nernst experimented on filaments made of magnesia, kaolin, chalk, etc., and with a hollow filament of magnesia obtained as high an efficiency as 0·96 candle per watt.

Such substances as those above named are, however, practically non-conductors at ordinary temperatures, but when raised, by independent means, to a sufficiently high temperature, ranging from 500° to 800° C., they not only become conducting, but are characterised by the large proportion of luminous rays which they emit. The rapid decrease in the resistance of the filament as the temperature and current simultaneously rise, tends to cause instability when running in parallel on circuit, and to make it very sensitive to variations of voltage. This is corrected by a series or steadying resistance made of fine wire having a resistance of 10 or 12 per cent of that of the whole lamp. Inclusive of the consumption in this resistance, such lamps absorb only from about 0·8 to 1·85 w.p.c., depending on the c.p.

The independent means for raising the temperature of the filament in order to make it conducting comprises what is called a *heating resistance* arranged close to the filament and in shunt to it. The current through the filament, when this begins to conduct, works a small cut-out in the resistance circuit, thereby opening it. The increase in conductivity of Nernst filaments with temperature is very rapid, and if that at, say, 500° C. be taken as 1, the conductivity at 700° C. is 5; at 800° C. it is 21; at 900° C. it is 61; at 1000° C. it is 120; and at 1100° C. it is 330. These filaments light up at about 950° C. We may now, with advantage, consider the form and construction of Nernst lamps, of which there are four types, namely: (1) The large type, pattern A; (2) small type, pattern B; (3) large

[1] 'Compressed-Air Manometer,' *N. Cimento*, 12. pp. 237-241 (1900).

type, Solar or Luna pattern, with flat horizontal filaments; (4) candle pattern, similar to the B type. These are all supplied by the Electrical Company of London and other firms.

Fig. 193 is a part-sectional diagrammatic sketch of the small-type, pattern B, Nernst lamp, showing connections. It consists of a porcelain collar or block P which carries the straight filament F (about 2·5 cms. long × 0·63 mm. diameter in a 220-volt lamp; about 2 cms. long × 0·4 mm. diameter in a 200-volt ¼-ampere lamp; and 3 cms. long × 1·0 mm. diameter in a 200-volt 1-ampere lamp) and also the spiral heating-coil H which surrounds it. These are connected together at one end K and to a split tube or socket N (shown to the left on the under side of P), the other ends being connected respectively to two additional tubes E and S (shown to the right), all securely carried by P. The arrangement which constitutes the filament and heater is shown very clearly by itself in Fig. 194, and a later form still in Fig. 195. The filament is connected to the terminal wires by means of a platinum bead[1] embedded by being fused into the ends (by an arc) in such a way that any shrinkage of the filament tightens the contact. The heater, which is expected to last from 2000 to 3000 hours, consists of a thin porcelain tube wound with fine platinum wire and painted with cement, the latter serving to protect the platinum from the intense heat of the filament. The connections to the rest of the lamp are made through three split rods carried by a hollow porcelain box B, and which slip into the three split tubes N E S referred to above. This porcelain box with its three rods is termed the contact-piece. Two of the rods carry contact guide-skates which make connection with the steadying resistance R when this is pushed in between them. The steadying resistance R (shown by itself in Fig. 196) consists of two or more fine iron-wire spirals supported in either an evacuated glass tube or a tube filled with inert gas, the ends being connected to two metal sleeves on the outside of the tube on opposite sides.

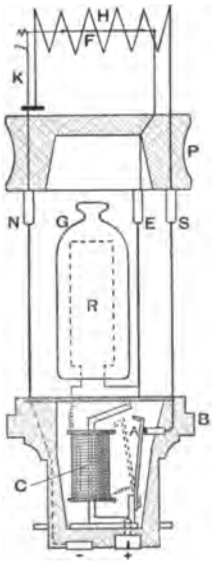


Fig. 193.—Sectional Diagram of Nernst Lamp, Type B.

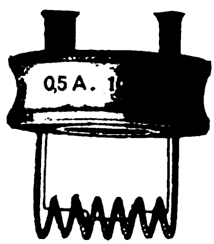


Fig. 194.—Filament and Heater.

[1] See *Elect. World and Engineer*, 43. pp. 981-985, May 21, 1904.

It is worked at such a temperature that a 10 per cent increase in the current increases this steadying resistance by 150 per cent. The porcelain box contains the automatic cut-out comprising a small electro-magnet AC, having an armature A capable of being attracted to, and held close against, one pole of the magnet. As shown in full line, Fig. 193, it is making contact with a connecting-stud, thus completing circuit through the spiral heater H. In the dotted position, it is attracted by the electro-magnet, thus breaking circuit through H and allowing all the current to pass through the filament F. The outside of the porcelain box has the two ordinary contact-blocks marked + and - on the end for making contact with the bayonets of an ordinary lamp-holder, and the two pins at the sides for fixing it in this holder. The complete lamp with lamp-case or guard, pattern B, is shown in Fig. 197. From the above description we see that the principal parts of a Nernst lamp are the *filament*, *heater*, *automatic cut-out*, and *steadying resistance*. Referring to Fig. 193, it will be seen that, on switching-on, the current enters at the +[ve] block, flows through H, and out at the -[ve] block. The heater H now glows dull red for some seconds until the filament F is sufficiently warmed to become conducting. The current through the filament circuit then becomes strong enough to cause the magnet AC to attract A, the heater circuit is

Fig. 195.—Filament and Heater.

Fig. 196.—Steadying Resistance.

Fig. 197.—Complete Lamp.

at once broken, the current passing then through the magnet coil C, – R, – filament F, and out at the – ve block.

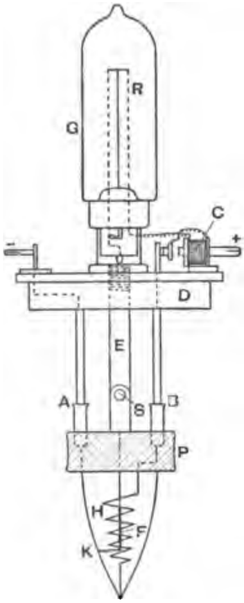


FIG. 198.—Diagram of Nernst Lamp, Type A.

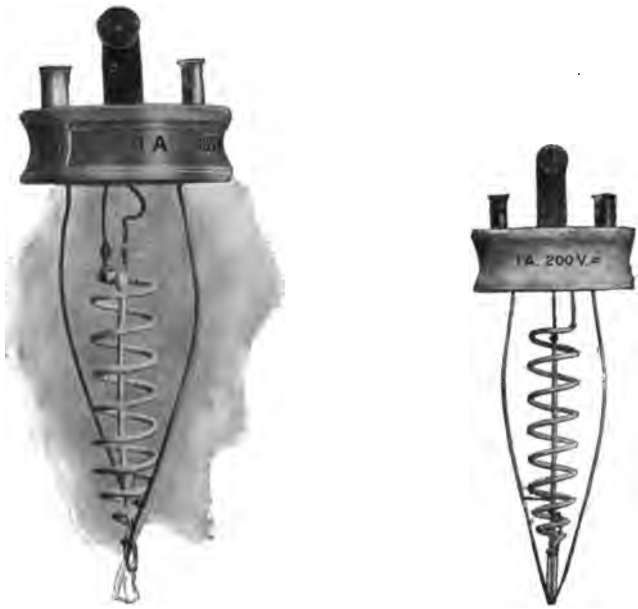
The above pattern B is suitable for replacing the ordinary glow-lamp in small rooms, and can be obtained for voltages from 100 to 250 volts, with candle-powers from 12 to 50, depending on the voltage; but where a better illumination is required, and in the case of public buildings, large halls, shops, factories, churches, and out-door use, the A type Nernst lamp is more suitable. It can be obtained for any voltage between 100 and 250, and for candle-powers from 60 to 170, and will last for from 400 to 1200 hours, and in many cases with an average of 750 hours. The arrangement and connections of this large type are shown in Fig. 198, and explain themselves. The steadying resistance R and filament with heater are depicted in Figs. 199 and 200-201 respectively. It will be noticed that the resistance R is enclosed in a metal-capped tube G, which is inserted in a holder similar to an ordinary lamp-holder. The flexible wire from the ceiling passes through the collar at the top of the frame (Fig. 202), and thence to the plugs seen on each side of the frame. These plugs, when pushed over the split terminal rods seen in Figs. 198 and 203, connect the supply to the lamp proper. The two outer contact-tubes, A and B, carried by the porcelain base P of the burner (Fig. 198), are slipped over the contact-rods on the porcelain base-plate D, and the centre contact-strips E are secured by a screw S.

FIG. 199.—Steadying Resistance.

The Solar and Luna Nernst lamps, for voltages from 110 to 200 and candle-powers from 125 to 250, differ from the A and B types in the form of filament and heater, which is shown in Fig. 204. The heater as seen is flat, and above the straight rod forming the filament, so that

it does not interfere with the downward distribution of light from the filament.

In all these lamps the filament and heater (which together may be called the burner) are both very fragile, and should not be touched by the fingers. Both burner and steadying resistance are marked with the proper current and voltage which each should have, and no two such parts should be used together which are marked with different currents. Further, the *sum of the voltages marked* on them should be equal to or slightly exceed the *maximum voltage* which the



FIGS. 200 and 201.—Filament and Heater, Type A.

circuit ever has, since overrunning a Nernst lamp shortens its life enormously without increasing its candle-power. In no case should it be possible for the circuit voltage to rise above the sum of the stampings by more than 2 per cent. Nernst lamps intended for direct current are rapidly destroyed if used with alternating current, and *vice versa.* Strict attention must be paid to polarity in connecting them to the circuit, or this will destroy them when used with direct current. The lamps should always be suspended vertically when possible, otherwise the time taken to light up is increased.

Owing to the high temperature (about 2500° C.) at which the filaments run, the light is whiter and more nearly like sunlight than any other illuminant. It is possible to obtain all sizes of lamps, from

12 c.p. with 1 filament to 2000 c.p. with multiple filaments. A 3-burner Luna Nernst lamp taking 3 amperes at 240 volts gives about 820 c.p., while another make of Nernst lamp of 2000 c.p. for 220 volts has 30 filaments. In the comparison of initial and running cost between Nernst and ordinary glow-lamps, there is said to be a saving of some 65 per cent in favour of the higher c.p. Nernst lamps, and of 40 per cent with low c.p. lamps. In both cases the saving is

FIG. 202.—Lamp-Case Frame.

greater the greater the cost of energy. In types A and B the steadying resistance, which should last for an indefinite time, absorbs 15 volts for lamps of from 96 to 150 volts, and 20 volts for lamps from 196 to 250 volts. It is interesting to note that a 220-volt filament taking 0·4 ampere has been found to require 20 volts more in the open air to make it glow properly than when burning with five others in a 3-inch globe, owing to the higher temperature of the surrounding air in the latter case.

In the case of direct-current lamps, the filament usually breaks at the $+^{ve}$ end: a black deposit, supposed to be 'platinum black,' is found at the $-^{ve}$ end.[1] Alternating-current Nernst lamps have a longer life the higher the periodicity of the current, *e.g.* an average

[1] Tests on Nernst Lamps (*Inst. Elect. Engin. Journ.* 31. pp. 1180-1196, June 1902).

life of 1300 hours is recorded by one user[1] of a batch of lamps for an alternating current making 125 ~ per second. There are, of course, numerous instances of an average life of 700 to 800 hours at 50 ~ per second, with some of 300 to 400 hours at 25 ~ per second.

Fig. 208.—Lamp-Case Holder complete.

Efficiency of Nernst Lamps.—According to Ingersoll,[2] the *absolute* luminous efficiency, *i.e.* the ratio of visible energy to the total energy consumed by 89-watt 110-volt lamps made by the Nernst Lamp Company, of Pittsburg, varies from 4·6 per cent in new lamps to 3·6 per cent in old ones, the temperature being estimated at 2360° C. The watts per candle diminish as the candle-power increases for the different types of Nernst lamp, and range from 0·8 to 1·85 watts per candle.

If the voltage given to a Nernst lamp be varied continuously and the current and c.p. measured simultaneously, a set of curves relating *candle-power* with volts, amperes, watts, apparent resistance, and watts per candle can be obtained, and which are similar to those obtained for an ordinary glow-lamp (Fig. 185) under similar conditions. Fig. 205 shows such a set for a lamp intended for a normal voltage of 165, and it is noteworthy that the lamp has a critical point at 168 volts which, if reached, the filament takes 0·5 ampere at 165 instead of the normal 0·27, and will burn out.

Vapour Lamps.—These lamps, first described by Arons,[3] are a development of very recent origin, and in principle are really arc lamps enclosed in a vacuum. In 1901 O. Lummer gave a description[4] of a mercury-vacuum lamp for spectroscopic work which contained improvements on Arons's form, and in which he worked with an arc about 3 cms. long, taking 16 amperes at 110 volts with a resistance

[1] *Amer. Electn.* 14. pp. 420-422, Sept. 1902.
[2] *Phys. Rev.* 17. pp. 371-377, Nov. 1903.
[3] *Wied. Ann.* 47. p. 767 (1892); and 58. p. 73 (1896).
[4] *Zeitschr. Instrumentenk.* 21. pp. 201-204, July 1901.

of 5 ohms in series. The possibilities before this type of lamp as an artificial source of light soon brought other workers into the field, for in the same year P. Cooper-Hewitt[1] described several forms of vapour lamps, and showed that the resistance of the vapour column approximately followed Ohm's Law, and that inefficiencies as low as 0·32 watt per candle could be obtained. The principle on which such lamps operate consists in dividing a column of mercury contained in an evacuated vessel, and which is placed in series with a resistance across the mains, into two parts. An arc is set up between the separated parts of the mercury column, which is maintained so long as the supply is kept on.

It may be well at this stage to describe one of the forms which vapour lamps have assumed for everyday use, namely, that developed

FIG. 204.—Luna or Solar Filament and Heater.

by Mr. C. Orme-Bastian, and shown diagrammatically in Fig. 206. It consists of the so-called *burner* B made of 'Jena' glass, and comprising a glass tube bent down at both ends and supported by the two arms X, X, from metal blocks N, K. A bulb G is formed at one end and a platinum wire is sealed through each of the extremities, thus forming the electrodes R, M of the burner B, which contains mercury to the extent shown by the dotted shading. The metal blocks N, K, supporting the burner, are carried by two brackets H, E, screwed to the ends of a bar L of insulating material. This bar L is pivoted at P to a fixed arm F, which is part of a fixed rectangular hollow frame F supported from the solenoidal coil C. The soft-iron plunger core T of this coil is hinged about a pin O to the bar L, and is capable of raising the left-hand end of the bar L (turning on the pivot P) when attracted up into the coil C. A balance-weight attached to L enables the centre of gravity of the bar L, with its

[1] *Elect. Rev. N.Y.* 38. pp. 513-515, April 27, 1901; and *Elect. World and Engineer*, 37. pp. 679-681, April 27, 1901.

attachments, to be adjusted so that the plunger T will be attracted and move up for a certain current in C. A set-screw stop S is also provided as an adjustment for the best position of burner B and core T when the lamp is not alight.

On closing the supply to the lamp, the current enters at the wire W marked +, which is connected to one of two terminal screws A

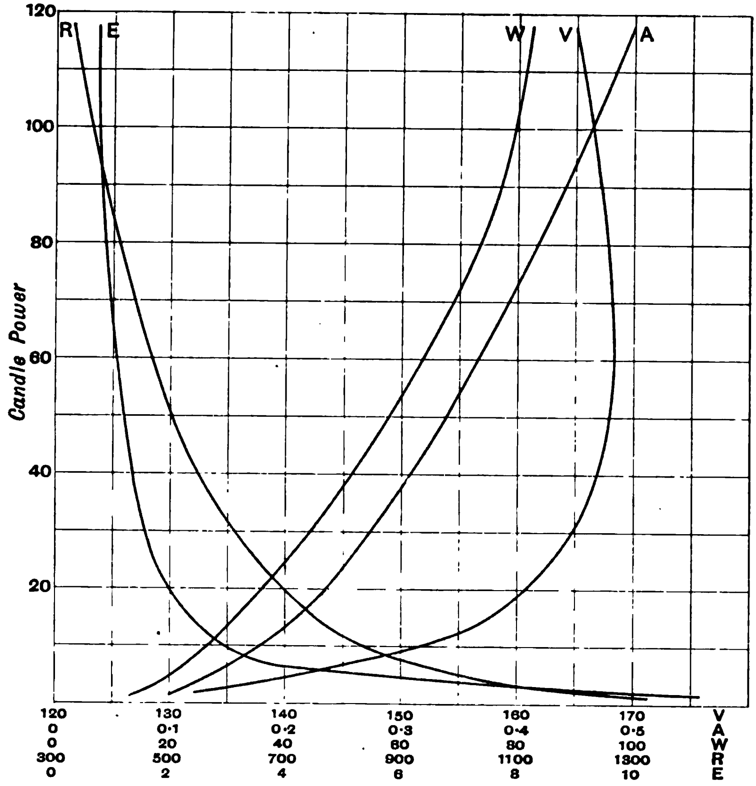


FIG. 205.—Curves for a 165-Volt Nernst Lamp.

fixed to a metal plate and carried by, but insulated from, the fixed frame F. From the second of these two terminals A it passes *via* E, K, *w*, M, B, R, *w*, N, H to the coil C, and through this to the wire W marked - and out of the lamp. In so doing, the plunger core T is attracted up into the energised solenoid C, so lifting the bar L and tilting the burner-tube B. The mercury column in B is thus broken by reason of some of the mercury flowing into G, and the arc is struck or set up inside B between the parted ends of the mercury columns, and is maintained so long as C remains energised by the current

flowing. When the switch in circuit is opened, T drops and mercury

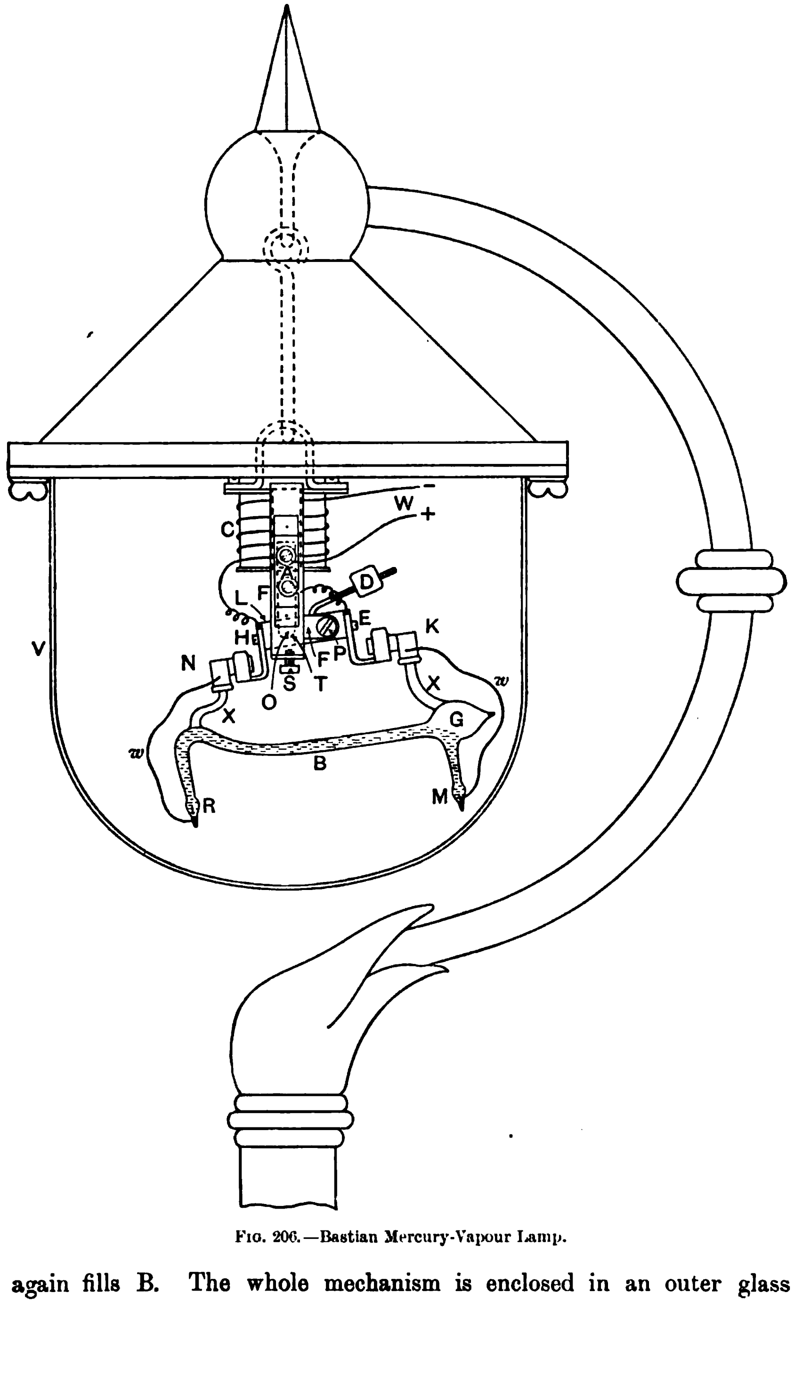


FIG. 206.—Bastian Mercury-Vapour Lamp.

again fills B. The whole mechanism is enclosed in an outer glass

globe V, which is easily removable from the frame of the lamp-top.

Fig. 206 shows the burner and tilting device in its normal or unlighted position. As the arc warms up the resistance of the mercury vapour increases after reaching a certain critical temperature, and the pressure of the mercury vapour alone would retain the mercury in the reservoir G independently of the fact of the tube B being tilted. The vacuum in the burner system need not be very perfect, because if a small bubble of air is left in, it can be shaken out of the mercury into the reservoir G, where it will remain and will not interfere with the action of the arc in B. Mr. Bastian prefers a little air in the burner, because it acts as a cushion for the mercury in transit. These vapour lamps can be arranged to burn on any voltage from 50 to 250 volts, but are most satisfactory at the higher voltages. A *series resistance* which absorbs about 25 per cent of the whole power taken by the lamp is connected in series with it. The efficiency of a lamp giving 140 candle-power is about 2 to 2½ candles per watt, taking into account the watts spent in series resistance and arc, while the life varies from 2700 to 3000 hours. The cause of failure at the end of the life is usually the cracking of the glass near the negative electrode R, which, however, does not usually result in a spilling of mercury. The glass of the burner does not blacken, but becomes slightly yellow in appearance with time. Bastian vapour lamps are in use in a number of places, having proved themselves satisfactory after careful tests.

Mr. P. Cooper-Hewitt [1] has shown that in his vapour lamp the vapour column approximately follows Ohm's Law. Vapour lamps may be said to be of two kinds, namely, those depending upon *conduction with* and *without* an *arc* respectively. The Cooper-Hewitt lamp belongs to the latter kind, one form consisting of a tube about ¾ in. in diameter and 2 or 3 ft. long. The upper or +^{ve} electrode is an inverted cup of iron, the lower or −^{ve} electrode being mercury only, a small portion of the surface of which is exposed in order to avoid flickering. Certain vapours and gases are, under suitable conditions, able to conduct a current of electricity on the application of a moderate E.M.F. after a current has once passed, and this is also the case if certain substances—*e.g.* sulphur and its compounds, such as sulphide of mercury, also selenium and phosphorus with mercury—be added to the lamp during manufacture. On the other hand, certain substances, particularly oxygen, should be excluded.

[1] *Elect. Rev. N.Y.* 38. pp. 513-515, April 27, 1901; *Elect. World and Engineer*, 37. pp. 679-681, April 27, 1901; and 38. pp. 503-509 (1901).

The spectrum of materials decides which are best suited for a light-emitting source, and while mercury vapour is suitable in many ways, it lacks in red rays. If the lamps are made to give a redder light by, *e.g.*, the use of sodium or potassium amalgams for the electrodes, their efficiency is smaller. In the process of manufacture, the tube containing the mercury and added substance is simultaneously heated, exhausted, and subjected to a current at a high E.M.F., and when it rises to intense brightness it is sealed off. The lamp should then light up on a moderate voltage without the external application of warmth for the purpose of reducing its effective starting resistance. The high initial resistance of the lamp is diminished, enabling the lamp to light at low voltages, by surrounding the glass near the $-^{ve}$ electrode by a band of metal foil connected electrically to the other electrode, thus positively charging the surface of the lamp exterior to the $-^{ve}$ electrode; and for alternating currents two such bands are used, one near each electrode. These bands reduce the high initial resistance occurring at the $-^{ve}$ electrode at starting, and which diminishes rapidly when current begins to flow. It is found that the degree of vacuum affects the regulation of the lamp; for the resistance of the vapour decreases with decrease of density to a certain point, and then increases as the vacuum becomes more perfect. The resistance of the lamp, as might be expected, varies inversely as the current and as the diameter of the tube.

Mr. Hewitt has made lamps on the above principle giving from 10 to 3000 c.p., with inefficiencies as low as a $\frac{1}{4}$ watt per spherical c.p. Recently he has devised a new form of the lamp[1] suitable for photographic use. In some tests[2] carried out by F. Schabinger on a 3-ampere 110-volt Hewitt vapour lamp with an arc about 45 ins. long, it was found that the c.p., as deduced and measured from a length of arc of 2 ins. in the middle, fell off rapidly in the first 24 hours, the watts per candle increasing from 0·5 to 0·61. The lamps have a life of from 800 to 1200 hours or more, failure in the end being caused by bad vacuum due to admission of air at the leading-in wires. In time the inside of the tube is coated with first a grey and then a black deposit, which may be due to some change in the oxide of lead of the lead-glass used.

Mr. C. P. Steinmetz[3] has described an ingenious device introduced by Weintraub for enabling mercury arcs to be run in series even with a supply voltage which varies as much as 40 per cent. A mercury

[1] *West. Electn.* 34. p. 421, May 21, 1904.
[2] *Elect. World and Engineer*, 43. p. 1194, June 25, 1904.
[3] *Elect. World and Engineer*, 41. pp. 316-317, Feb. 21, 1903.

arc in a vacuum requiring about 80 or 90 volts will, as already pointed out, have a length of 4 or 5 ft. Such a lamp is usually started by a high-voltage discharge in the manner indicated above, which precludes the operation of several in series. Weintraub's arrangement enables several lamps of only 12 or 18 ins. long to be operated in series, not only efficiently, but with considerable stability. A similar device has been patented by Mr. J. T. H. Dempster, and is described in the *Electrical World and Engineer*, 45. p. 349, Feb. 18, 1905.

The nature of the glass employed in mercury vapour lamps has an important bearing on their efficiency and life. This will be gathered from the foregoing remarks, and is still further emphasised in a paper on mercury-vapour lamps by S. Strauss,[1] in which he mentions the behaviour of quartz-glass made by a special process. Though expensive, such glass enables a fall of volts amounting to 4 volts per cm. length of path to be obtained with a small diameter of tube, whereas ordinary glass allows of only about 0·7 volt per cm. Moreover, quartz-glass has a melting-point some 800° higher, and therefore does not soften through the heat of the arc, or crack through too sudden cooling of the lamp. The use of quartz-glass results in a lower efficiency, which is stated to be about 1·1 watt per candle as against 0·4 with other glass, and further, it is attacked by substances such as lithium, potassium, or rubidium used in the lamp to improve the colour of the light.

QUESTIONS ON CHAPTER VIII

[*Supplement all Answers with Sketches when possible.*]

1. Describe in detail, with sketches, the best method with which you are acquainted for making a glow-lamp. (Hons. Sect. III. C. and G. 1898.)

2. Describe what you know about efficiency, life, effect on the eyes, etc., of 200-volt glow-lamps as compared with 100-volt lamps giving the same illumination. Consider whether it pays a consumer to replace 100-volt with 200-volt lamps if the price charged by the Supply Company per B.O.T. unit be reduced by one-quarter. (Hons. Sect. II. C. and G. 1899.)

3. A theatre lamp-regulating resistance is capable of producing the desired gradations of light when used to control a group of 50 16-c.p. 100-volt lamps. Would the same regulating resistance produce equally satisfactory results if used to control the same number of 16-c.p. 250-volt lamps? If not, why not? Would it produce the same results with regard to relative brilliancy of individual lamps with a group of any other number of 250-volt 16-c.p. lamp, and if so, of about how many lamps must this group consist? (Prelim. C. and G. 1900.)

4. What is the principle of the construction and action of the Nernst lamp? What are its advantages and disadvantages as compared with glow and arc lamps? (Hons. Sect. II. C. and G. 1900.)

---

[1] *Zeitschr. Electrotechn. Wien*, 23. pp. 141-147, March 5, 1905.

5. How does the light given out by a new glow-lamp vary with the potential difference maintained between its terminals? If two batches of the same kind of lamps be run for 400 hours at two constant pressures respectively, one being the pressure for which the lamps were intended, and the other, say, a pressure 3 per cent higher, will the same relationship between the P.D. and c.p. hold as at first? If not, what sort of relation may be expected to hold, and why is it different from that which existed when the lamps were new? (Ord. C. and G. 1901.)

6. Describe briefly the Nernst incandescent lamp, with its necessary parts and their uses. (Prelim. C. and G. 1903.)

CHAPTER IX

ELECTRIC ARC LAMPS

Introduction.—There remains still another method of producing artificial illumination by means of electricity, and to this we must now turn our attention. If two carbon rods or pencils, forming the extremities (*i.e.* electrodes) of an electrical circuit which contains a source of current at a sufficiently large E.M.F., be made to touch momentarily and then separated slightly, an extremely bright light is produced between the points thus separated. The current set up by the momentary contact continues to flow, after separation, across the short air-gap, and, if the pencils are held in line and horizontally, the flame so produced will curve upwards in the form of an *arch* between their ends, due to the stream of hot air rising. Further, owing to the E.M.F. of the source of electricity being obtained by means of a battery of voltaic cells, the light in its earlier stages was therefore known as the 'voltaic *arc*.' With the electrodes placed vertically, as they are now in all but one instance, there is no arching of the flame; but the abbreviation 'arc' for arch is still retained, and the effect is now known as, simply, the *arc* light.

The phenomenon of the electric arc was first shown by Sir Humphry Davy (about 1808), before the Royal Institution. No development, however, of a very striking nature took place until after the invention of the dynamo (about 1867-70), probably for the want of a more economical source of current than primary cells, hitherto used. The trend of invention has, of course, been to employ electro-mechanical means for bringing the carbons together momentarily, then separating them slightly, and afterwards maintaining them at approximately the same distance apart. Such an arrangement is now commonly known as an *arc lamp*, and the number of different forms invented up to the present time is very great.

Choice of Electrodes. Phenomena in producing an Arc.—Returning now to the phenomenon of the arc itself. When an arc

is set up between two electrodes, their ends commence to glow and at the same time volatilise. The temperature at which volatilisation takes place determines the intensity of the light emitted, the latter increasing with the former. Moreover, *all matter*, when raised to the *same* degree of *temperature*, becomes *equally luminous*. Hence we see the importance of choosing a material for electrodes which has as high a temperature of volatilisation as possible, since this is the highest limit to which the temperature of that body can rise. For this reason, carbon is the material invariably used, it being a non-metal which cannot be melted or fused by heat into a liquid state, while it volatilises, or passes into a gaseous state, only at a very high temperature, and with a minimum expenditure of electrical energy. All the metals are precluded from adoption on account of their low temperature of volatilisation as compared with that of carbon, and from the fact that their temperature of incandescence is so very near to their temperature of fusion, while the intensity of their incandescence is obtained with a much greater expenditure of energy than in the case of carbon.

The foregoing remarks will serve to emphasise the importance of the quality of carbons used, on the efficiency of the arc as a light-emitting source; for the admixture of even small quantities of impurities, in the form of *any* foreign substance, lowers the temperature of volatilisation, and therefore the intensity of the light, for the same expenditure of electrical energy. The presence of impurities in the carbons not only diminishes the light and affects its colour or quality, but represents a wasteful consumption of energy; for they have to be volatilised, and pass across the arc without emitting the light which would be evolved by a similar amount of carbon volatilised by the energy which they absorb. Such impurities, when present, condense on the $-^{ve}$ carbon, giving it the appearance of having little growths on its surface. The carbons should therefore be as pure as possible, and homogeneous or regular in density throughout their entire length and cross section, the latter property tending to minimise flickering of the arc.

At the present day, only specially prepared carbons are used for arc lighting, these being made from a specially prepared mixture, which is formed into rods by being either moulded in moulds or forced through a die. The latter method, particularly, ensures maximum uniformity in density and electrical conductivity, which last-named property is of much importance, being often still further increased by coating the carbon with a very thin film of copper deposited by electrolysis. Metal-coated carbons are used to some extent in heavy current arcs

in order to diminish the absorption of pressure in the carbons themselves. The metal coating must, however, not be too thick, otherwise, in melting, it will cause an obnoxious colouring of the arc as the carbons consume away, and, further, it might drop in globules on to the glass globe containing the arc and crack it.

The conductivity of ordinary uncoated arc-light carbon varies with the maker, process, and type of carbon. Denoting this in terms of the reciprocal quality (p. 81), the resistance is from fifteen to twenty times less than that of ordinary common impure gas-retort carbon, and ranges from 0·15 to 0·175 ohm per foot for a present-day arc-light carbon about 13 mm. diameter. For a detailed description of the process of manufacture of arc-light carbons the reader should refer to one or more of the special treatises[1] on this subject.

Now the operation of producing an arc by bringing the two ends of a pair of carbon electrodes together and then separating them is commonly known as 'striking the arc.' When the electrodes (commonly termed 'the carbons') touch, the current passing through them causes the junction to become very hot, and on separating them the spark produced, volatilises some of the carbon. The vapour thus occupying the interpolar space sufficiently reduces the resistance of this latter to enable the P.D. between the carbons (now existent) to maintain the passage of electric current between them. This current very quickly increases the foregoing effects, raising the temperature and luminosity to their highest limits. The reason for first making the carbons touch is because it would otherwise require a much greater E.M.F. in the circuit to start an arc across even the thinnest film of air-space between them.

The Crater, Temperature, and Form of an Electric Arc.—The stream of carbon vapour between the carbons has the appearance of a violet-coloured flame, which is not, however, the chief source of light; for, owing to solids being better radiators than gases, and to the much higher temperature of the carbon tips than the vapour, the carbons give by far the largest proportion of the light. The carbon *from* which the current flows across the arc (called the +^{ve} carbon) is supposed to be at a temperature somewhere between 5000° C. and 6000° C., while the carbon *to* which it flows after crossing the arc (called the −^{ve} carbon) is at a lower temperature, probably between 2000° C. and 3000° C. The +^{ve} carbon therefore volatilises and consumes away at a greater rate than the −^{ve}, some of the vapour from the hotter +^{ve} condensing on the colder surface of the −^{ve}

[1] *The Manufacture of Electric Light Carbon*, by O. G. Pritchard ('The Electrician' Publishing Company, London).

carbon. The effect of this is to cause a shallow cup-shaped cavity to be formed at the end of the $+^{ve}$ carbon, due to the temperature being greater at its centre, and which is called the *crater*, while the $-^{ve}$ carbon assumes and burns away in the form of a cone with its apex somewhat flattened.

What we have just remarked is true for arc lights produced by continuous currents. If, however, a so-called alternating current, *i.e.* one reversing its direction, say, 50 or 100 times a second, be used, which is also capable of producing an arc light, then each carbon assumes a conical form similar to that of the $-^{ve}$ in the direct-current arc. This arises from each carbon rapidly becoming alternately $+^{ve}$ and $-^{ve}$; and both carbons assume, roughly, the same temperature, consuming away at equal rates. One or two makes of alternating-current arc lamps have been made to work with a rate of reversal of the current as low as twenty-five periods per second, but forty appears to be about the lower limit in most cases.

The rate of consumption of the carbons in an electric arc does not, however, only depend on whether the current is continuous or alternating, but also on whether the arc is burning in the open air or in a tightly-fitting enclosing globe, on the diameter of the carbons, and on the current they are carrying. For $+^{ve}$ and $-^{ve}$ carbons of the same kind and of equal diameter, other things being the same, the rate of consumption of the $+^{ve}$ is, roughly, double that of the $-^{ve}$ for continuous current, whether the arc is *open* or *enclosed*. With longer arcs, this excess of consumption of the $+^{ve}$ over that of the $-^{ve}$ carbon is less, and more uniform than in shorter arcs. By, however, having a $-^{ve}$ carbon of suitably smaller cross section than that of the $+^{ve}$, the rates of consumption can be made equal, less light being obstructed by the $-^{ve}$ and a greater volume obtained in a downward direction, the $+^{ve}$ carbon being uppermost, as it is in all ordinary cases. Furthermore, the carbons of an enclosed arc consume away at the rate of about $\frac{1}{16}$ in. per hour, and will last from five to ten times longer than similar carbons in an open arc, everything else being the same in the two cases. The optical efficiency of the enclosed arc is only some 60 per cent of that of the open arc. For continuous currents the $+^{ve}$ carbon is usually *cored*, *i.e.* a hole about $\frac{3}{32}$ in. diameter is left in the centre of the carbon from end to end during manufacture, this hole being afterwards filled up tightly with fine graphite. The object of this is to induce the crater to keep centrally in the carbon and thus produce a uniform illumination all round. But for this, the crater often works to one side of the carbon, thus casting shadows. The diameter of carbon to be used for different currents

varies with almost every maker, but ranges from 8 mm. in 3-ampere lamps to 25 mm. in 20-ampere lamps. The $-^{ve}$ is from 4 to 7 mm. smaller in diameter than the $+^{ve}$ carbon. Depending on the type of lamp and carbons used, enclosed arcs burn for a maximum of about 150 hours with one retrim, though 80 to 100 hours is more commonly guaranteed. Open arc lamps are now made which will burn from 40 to 70 hours with a retrim, but from 16 to 30 is the more common life.

Owing to the high temperature of the arc, even the most refractory substances, such as flint, diamond, platinum, etc., previously supposed to be infusible, can be easily melted in it. An application of the great heat of the arc to industrial purposes is to be found in all electrical furnaces for smelting and other purposes and in the production of calcium carbide, aluminium, etc.

Back E.M.F. of the Arc.—An interesting phenomenon exists in connection with the electric arc, namely, that it does not behave altogether like a simple resistance, but exerts a counter or back E.M.F. of its own in addition to possessing a certain ohmic resistance. This back E.M.F. opposes the impressed E.M.F. which creates the arc, and appears to have a value always ranging between 30 and 40 volts. The actual impressed E.M.F. therefore necessary to maintain an arc is the back E.M.F. plus the fall of potential (CR) in the arc due to the current C flowing through its ohmic resistance R. This latter resistance varies almost directly proportional to the distance between the carbons. Probably one of the most likely explanations of this phenomenon of back E.M.F. in the arc is that suggested by Professor S. P. Thompson, which in substance is as follows: Electrical energy is expended in volatilising a certain proportion of the $+^{ve}$ carbon, which is subsequently condensed on the $-^{ve}$ carbon. In this transformation of the carbon from the solid to the gaseous state, a certain quantity of heat (termed latent heat) is absorbed by the vapour without its temperature rising. This vapour, in condensing on the colder $-^{ve}$ rod, parts with the same quantity of latent heat, and in so doing develops, in the reverse sense, the electrical energy which initiated the transformation, thereby causing a back E.M.F. From the foregoing remarks it follows at once that, in order to operate an arc successfully, the impressed voltage, supplied to the lamp from the source, must always exceed the value of the back E.M.F., which is generally taken to be about 39 volts.

Length of Arc: Its Ohmic and Apparent Resistance.—Now this back E.M.F., which acts as an obstruction or resistance to the supply current, is one of two factors in what may conveniently be termed the *apparent resistance* of the arc. The other factor is the *ohmic resistance*

of the air-space separating the carbons, which may amount to any value between $\frac{1}{10}$ and 10 ohms, depending on the length of arc. Taking the frequently assumed value of this for ordinary short arcs burning in air to be about $\frac{1}{2}$ ohm, as in a so-called 'open-type' arc lamp, and the current to be 12 amperes, we see that 6 volts are needed to overcome this resistance. The pressure absorbed in the arc under these circumstances would therefore be 39 + 6, or 45 volts, which indicates that, unlike the ordinary glow-lamp, a minimum of from 45 to 50 volts must be provided as an impressed supply to operate an electric arc satisfactorily.

In present-day practice the length of arc may be normally anything from $\frac{1}{10}$ to $\frac{1}{2}$ an inch, depending on the type of lamp; lengths bordering on the former figure being 'short arcs,' those on the latter being 'long arcs.' Now it has previously been remarked that the ohmic resistance of the arc increases nearly proportionally to the air-gap, and hence the voltage absorbed in sending the current through the air-space is nearly proportional to the length of this space. Consequently we find the 'long-arc' type of lamp at the present day taking as much as 75 to 100 volts, and in a certain instance of even 160 volts, across the arc (with an arc $\frac{3}{4}$ in. long) from the source of supply for their satisfactory operation. In the case of the 'short-arc' type of lamp particularly, if the arc becomes temporarily shorter, from any cause, than its normal value, *hissing* and instability usually take place, while the back E.M.F. also diminishes and becomes unstable. On the contrary, if the arc becomes abnormal in length, *flaring* occurs, the flame travelling round the arc at the sides and causing irregular illumination.

Maintenance and Regulation of an Electric Arc.—Now since the quantity of light developed by an electric arc is increased or diminished in proportion to the amount of electrical energy absorbed by it, a steady or constant illumination and good efficiency will only be obtained by maintaining the amount of energy transformed in the arc constant. From our definition of energy, given on page 58, it will be seen, therefore, that the fluctuation of electrical power, and consequently of the two factors (amperes and volts) of this power, supplied to an arc lamp must be allowed for. Now electrical power is supplied for lighting or other purposes nowadays in the form of (1) constant pressure, the current varying to suit the demand; (2) constant current, the pressure varying to suit the demand. The first of these is termed the *parallel system*, in which the lamps are all in parallel across the supply mains; the second is termed the *series system*, in which they are all in series with one another and the supply.

The energy transformed in the arc must therefore be maintained constant by means of automatic mechanism controlled by the variable factor of the power absorbed in the lamp, whether current or voltage.

Since, however, any change of energy is to be prevented or minimised by the operation of the mechanism, this last-named must itself be set in motion by the changes in the variable factor. For example, an arc lamp requires normally 5 amperes at a constant P.D. of 100 volts; if the current suddenly increases from any cause to 5·5 amperes, the additional 0·5 ampere must set the regulating mechanism in motion for reducing the current again to 5·0 amperes. In a well-designed lamp nowadays the mechanism is so simple and well made that only a small fraction of the total energy transformed in the arc is expended in regulating or maintaining the arc-energy constant. It should be remembered that the *current* varies *inversely*, and the *voltage directly*, as the *length of arc*, and hence fluctuations are caused mainly by the variation in the length of arc due to the consumption of the carbons.

Desiderata of Regulating Mechanism: Functions performed by it.—The exacting requirements in a mechanism such as referred to above, and which is the crux of the whole matter, makes one wonder at the fine state of perfection of steadiness attained in arc lamps of to-day, for this can only result with a mechanism which is (1) simple, well made and designed, and hence unlikely to get out of order with time or rough usage; (2) light, compact, and of small inertia, and therefore capable of rapid motion from rest, or *vice versa*; (3) sensitive to small fluctuations of arc energy; (4) insensitive to dust, dirt, and moisture on its parts; (5) lastly, it must, as a whole, be capable of the following operations, namely:—

(*a*) Causing or allowing the carbons to touch initially;

(*b*) Separating them, *i.e.* of striking the arc;

(*c*) Feeding them towards one another as they consume away;

(*d*) Combining actions (*b*) and (*c*), *i.e.* maintaining the energy transformed in the arc constant

And, in lamps to be used in series with one another,

(*e*) Substituting, or 'cutting in,' a resistance across the lamp terminals equivalent to that offered by the lamp while working normally, thus preventing the other lamps in series being put out or the current strength affected in the event of the complete consumption of carbons or of them being accidentally prevented from approaching one another.

Gravity and one or more of the properties of an electric current

(p. 35) are the only forces controlling the mechanism in operations (*a*) to (*e*).

Operation (*a*) is usually performed by the upper carbon gravitating on to the lower one.

(*c*) is very often done in the same way, the feed, however, being imperceptibly small and controlled by the friction of a brake or clutch which is actuated electrically.

Operations (*b*), (*d*), and (*e*) are effected electro-magnetically in all but one instance, and in this it is done electro-thermally. With the exception of this instance, (*b*) is always done by an electro-magnet, or solenoid, connected in series with the arc and wound with a few turns of sufficiently thick insulated wire to carry the lamp current. This is sensitive to current fluctuations, and is capable, when carrying the normal current of the lamp, of maintaining an arc of a certain length.

In many types of lamps this so-called *series* coil, combined with the above-mentioned brake, constitutes the feed-mechanism for operation (*c*). Otherwise, feeding is effected by a separate electro-magnet, or solenoid, connected across the arc and wound with many turns of fine wire having a large resistance. Such a coil is sensitive to P.D. variations between the carbons. With this method an increase in the length of arc increases the P.D. between the carbons, and hence that at the terminals of the *shunt coil*, as it is called. This coil thus takes more current, becoming stronger and pushing the carbons closer together.

Sometimes both a series and shunt coil act on the carbons, being arranged in such a way that the series coil separates and the shunt coil feeds. The arc in this case takes such a length that the energy transformed in it is always a constant quantity, the series and shunt coils producing equilibrium in the moving parts at this moment. Such a lamp is called a *differential* arc lamp, and satisfies case (*d*) above.

Lamps for use on a constant-current circuit are provided usually with merely a shunt coil and cut-in electro-magnet, while those for use on constant potential circuits usually have only a series coil. Where both current and voltage are liable to vary even though one of them is supposed to be the constant, a differential arc lamp will give the best results.

Modern Arc Lamps.—To attempt to make any useful classification of arc lamps, as they exist to-day, is practically impossible. This is not because there is such a great variety of forms in existence, but because the various characteristics, *e.g.* forms of brakes, clutches, windings of coils for constant P.D. or current circuits, and lengths of

arc, etc., are common to the different makes. For instance, the same make and form of lamp can be made with a series or a shunt or a differential coil: the only alteration necessary is the winding. Similarly with but slight alteration in the globe, an *open* or *enclosed* type of lamp can be produced.

We shall therefore now consider in some detail a few types of prominent arc lamps differing somewhat in the arrangement and construction.

The Davy Enclosed Arc Lamps.—These lamps, made by Messrs. Arc Lamps Ltd., are all practically of the same design, whether for alternating or direct currents, series or parallel working. The lower or $-^{ve}$ carbon N is fixed, while the upper or $+^{ve}$ carbon is actuated by a very simple clutch-mechanism controlled by the current flowing in a solenoid. The action and general arrangement of parts will be understood from a reference to the diagram shown in Fig. 207. The top cover T of the lamp carrying the suspension-insulator K is rigidly connected with the floor D of the lamp by a stout metal tube B in which slides the holder (not shown) into which the upper carbon R is pushed. To the outside of the tube B is pivoted at V a lever or rocker arm A, to which is attached at one end the connecting-rod G of the clutch and piston-rod H of an air dash-pot P, and at the other end a spring S and a link L supporting the plunger core C of the solenoid M. The rod G is rigidly fixed at its lower end to an inverted movable U-shaped block F, between the limbs of which is freely pivoted a ring-clutch E shown in plan in the lower sketch. The ring portion encircles the upper carbon rod R quite freely when horizontal, its projections on opposite sides passing also freely through two vertical slots in the opposite sides of B. These help to centralise the clutch-ring and rod R, the ring being horizontal when rest-

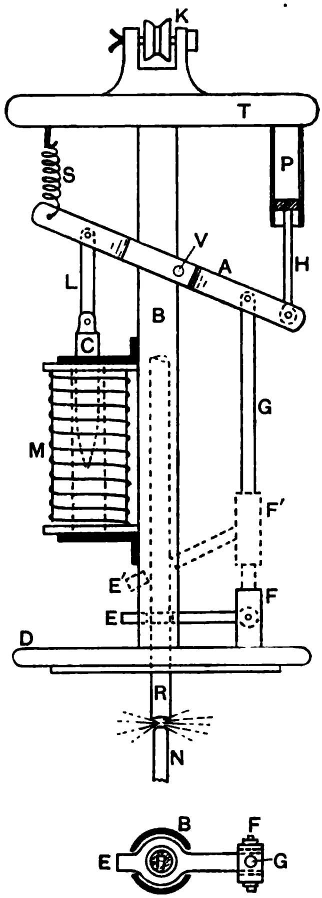


FIG. 207.—Diagram of Working Parts of Davy Enclosed Arc Lamp.

ing on the bottom of the slots. This is the position E when no current flows through the lamp, but if current be switched on to it, the core C, which is coned to equalise the strong pull of M on it through the long distance required, draws C down and F up bodily. The clutch-ring E is thus tilted, and, gripping R, rises bodily with it to position E′F′, so striking the arc. The spring S acts like a shunt coil, for it tends to lower G, and with it the clutch-ring, so as to let R very gradually glide through and feed the arc when too long. The only difference in the alternating-current lamp is that it is worked off a *compensator* which supplies the necessary voltage to the lamp. The bobbins are also split and the core C well laminated to minimise eddy currents in them, while the link L is replaced by a spring to prevent the lamp chattering.

FIG. 208.—Photo of Davy Arc Lamp (direct current) showing Working Parts.

Some four or five years ago, Mr. W. J. Davy patented the silencing arrangement now used in his alternating-current lamps, which consisted in suspending the whole of the internal portion of the lamp from the top by a spring. The effect of this is, that if the lamp commences to vibrate and hum, the springs will do so also; but the two cannot keep in step or synchronism with the reversals of current, so that the noise ceases.

It may also be noted here that the coil of an alternating-current lamp must have a larger number of turns, and its core a larger cross-sectional area of iron, than would be required for the same lamp used with direct current, owing to the smaller magnetic effect of the alternating current. For the same magnetic force exerted, therefore, an alternating-current electro-magnet is larger than one for direct current.

The spring S is only used in lamps intended to work in series on circuits over 100 volts. The direct-current lamps work perfectly, five in series, across 500- to 550-volt tramway circuits, but in this case

their circuit is protected by an automatic cut-out not shown in Fig. 208. The alternating lamps run singly on 100 to 120 volts, or singly and also two in series, with compensator in either case, on 200 to 220 volts with choking coil. The arrangement in the two cases is shown in Figs. 209 and 210. Fig. 208 is taken from a photograph of a Davy direct-current enclosed arc lamp with hood and globe removed.

Exactly the same mechanism is employed in the Davy *twin arc lamp* shown in Figs. 211 and 212, which are taken from photographs. The only difference is that two similar clutches (instead of one) are used, connected to the one controlling arm, which is actuated by

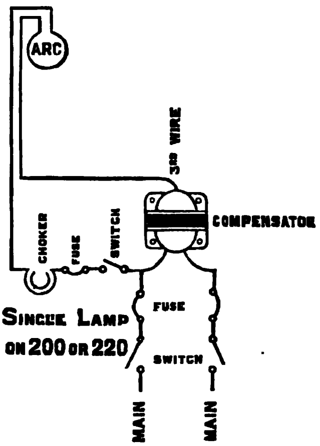


FIG. 209.—Single Lamp with Compensator.

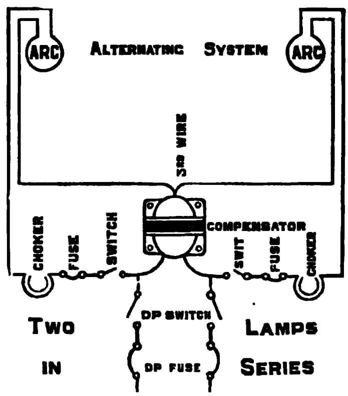


FIG. 210.—Two Lamps with Compensator.

a U-shaped core attracted into two solenoids side by side. In this twin lamp both arcs are struck together, the current flowing through them in series, so that the lamp can be run singly on 200 to 240 volts, or two in series on 400 to 420 volts, with a self-contained resistance which is wound on four vertical pillars seen at the sides in Figs. 211 and 212.

The length of arc for both direct and alternating current should be from $\frac{3}{8}$ in. to $\frac{1}{2}$ in.; and if the arc is longer and goes out in a few minutes after switching on, more resistance or choking must be inserted in series with it. The arcs of lamps in series can be brought to the same length by increasing the tension of the spring S in the lamp with the long arc, or the opposite in the other lamp.

The use of arc lamps for the interior lighting of buildings is always accompanied by shadows cast by obstructions when these

latter exist, as in factories, etc. The shadows are objectionably dark in comparison with the otherwise brilliant illumination, but can be avoided, where whitewashed ceilings exist, by using a so-called inverted reflecting arc lamp, the Davy form of which is shown in

FIG. 211.—Davy Twin Arc Lamp.

FIG. 212.—Davy Twin Arc Lamp.

Fig. 213. With this, the light is thrown by a reflector under the lamp on to the ceiling and walls; these, when white, in turn reflecting the greater part of the light all over the room with a diffusion approximating to that of daylight.

The Stewart Arc Lamp.—This lamp is made by Messrs. Defries and Son, of London, in some three or four standard types, differing slightly in arrangement from one another, but all operated with

clutches which are controlled by solenoids. They are characterised by the absence of any rigid clamp in the clutch, the construction of which in each case precludes the possibility of it sticking. In lamps for direct-current circuits of 200 volts and over, the clutch consists of two linked parallel tubes between which the carbon-holder is either held or released according to the distance between them. This distance is varied by the motion of a rocking-lever actuated, in the case of lamps burning singly on constant-voltage mains, by a series-wound solenoid, and, in the case of lamps burning in long series, by the differential action of series and shunt solenoids. The motion of the mechanism is steadied in the usual way by a loose-fitting dash-pot. On the extinction of one out of a number of lamps in series, due to the carbons failing to feed or being exhausted, the shunt magnet closes a contact which throws a compensating resistance into circuit equal to that of the working lamp. The other lamps thus continue to burn on undisturbed—a result likewise attained by means of a hand-operated switch inside the lamp, which cuts out the lamp and cuts in the same resistance when the lamp requires retrimming.

FIG. 213.—Davy Inverted Reflecting Enclosed Arc Lamp.

The Stewart enclosed twin-carbon lamp is shown in part-sectional elevation in Fig. 214, and diagrammatically at the side. The lower or $-^{ve}$ carbons G are clamped in holders, supported at the lower ends of two fixed rods, inside an inner cylindrical combustion-vessel of glass (shown shaded in section). The mouth of this vessel is held up nearly air-tight against the floor of the lamp-box by a bail carrying a hollow button which presses against the bottom hemispherical end of the vessel. The tension of the bail is easily adjusted by means of nuts (not shown) on the eyes which carry it. The two thick wire rods supporting the inner vessel are seen in Fig. 214 just outside it, and an outer spherical globe encloses the above. The two upper or $+^{ve}$ carbons F are merely pushed up into, and held by, two upper holders which slide freely in the tubes B B. These carbons pass freely through the clutch-rings E when the latter are horizontal. The rings can rest on two fixed bracket-plates, and are attached by rods or cords to the U-shaped soft-iron core of the solenoids

C C, which core has also attached to it the piston of an air dash-pot D. The cut-out resistance referred to previously is wound on spools A A, and is fixed in the top of the lamp. The cutting-in switch alluded to is shown at the top of the small diagram of the con-

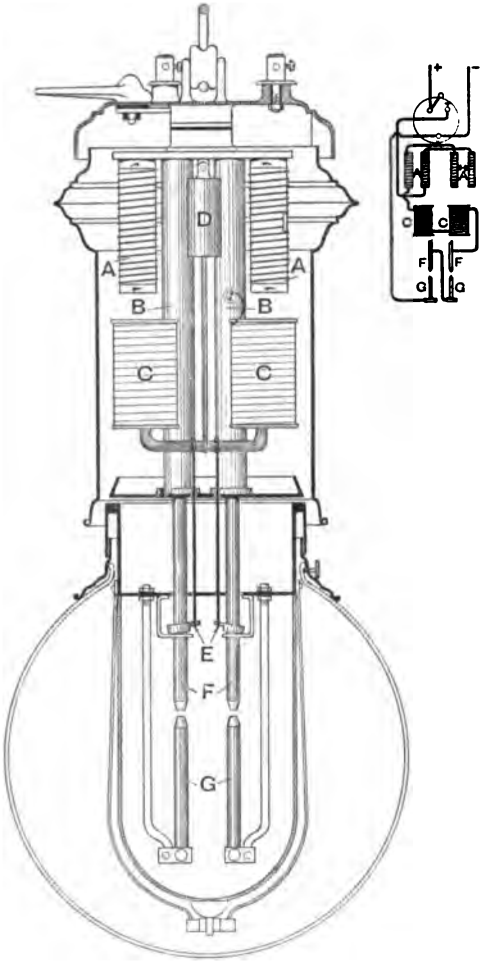


FIG. 214.—Stewart Enclosed Twin-Carbon Arc Lamp.

nections of the lamp, from which it will be seen that the two arcs are in series with one another. When current is switched on to the lamp, F F having previously gravitated on to G, C C suck up the core, thereby tilting the rings E E, which bind on the carbons, lifting them bodily. Both arcs are in this way *struck* simultaneously, and as the carbons

burn away C C become weaker, thus allowing E E to rest on the brackets and tilt back so as to let the carbons slide gradually but imperceptibly past the clutch-rings and feed the arcs. The principle of having two arcs burning in series in one lamp is, however, employed by other makers of arc lamps, and enables such lamps to be used much more economically than single arc lamps on high-voltage circuits.

For voltages in the neighbourhood of 100, a new type of Stewart lamp, called the 'High-Economy Arc Lamp,' has been introduced. In this the series resistance is replaced by a choking coil, with a saving of some 40 per cent in current according to some recent tests. This lamp is shown in Fig. 215, and consists of a clutch in the form of a loose ring D, through which the upper carbon passes. The ring binds on the carbon when tilted and raises it in the way already described, but when depressed again sufficiently the carbon is able to glide very gradually past it. The ring D is supported loosely, as shown, from a cross-bar which hangs by means of the two vertical rods from the yoke of the plunger cores of the solenoids E F. These are differentially wound with series coils E and shunt coils F, while a choking coil L is connected in parallel with the shunt and in series with the arc. With this arrangement, any change of current is felt in the shunt coils earlier than it is in the arc, by a time corresponding with the difference in self-induction between the choking and series coils, and the shunt coil.

By giving suitable proportions to the coils, this lag is made approximately equal to the time required for overcoming the inertia of the moving parts, so that their regulation occurs synchronously with the change of current in the arc. This arrangement, while introducing no mechanical complication at all, provides an electrical regulating mechanism which is not only permanent, but is also of far greater sensitiveness than that which has been attained by the use of resistances. Further, instead of it being necessary to absorb 25 to 30 volts in series resistance, as is the case with many enclosed arc lamps on 100 volts or so, these Stewart high-economy lamps burn with a difference of only 13 volts between line and arc.

The sensitiveness of the feed makes the lamp burn very steadily; and the use of two small resistances A K connected respectively with the series and shunt circuits, the P.D. drop in which is included in the 13 volts above, allows slight modification to be made in the voltage and amperage of the lamp. The choking coil can be fixed in the lamp or otherwise.

In alternating-current lamps the same clutch as shown in Fig. 214

is used with a series solenoid, elastic supports and connections being used wherever possible in order to remove the vibration common in many alternating-current lamps. With such an arrangement as the above, on, say, a 110-volt supply, the arc is longer than, and takes

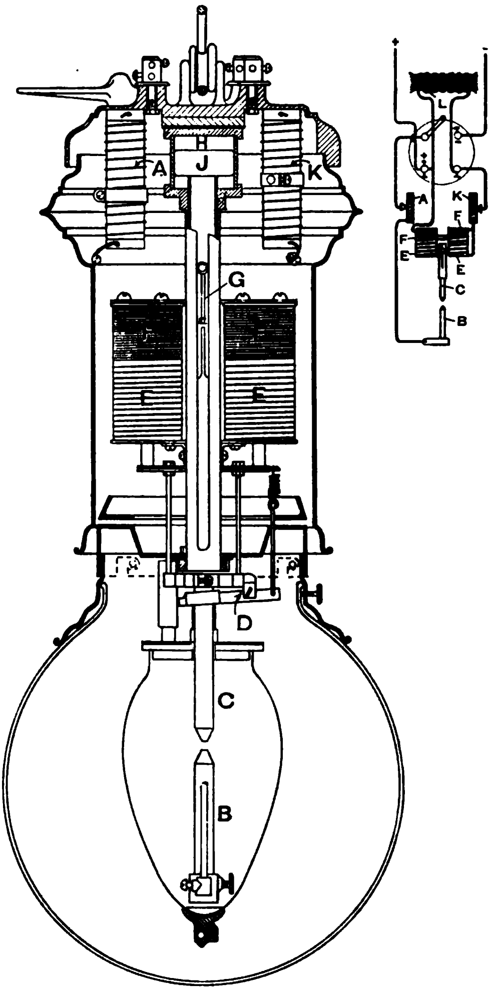


FIG. 215.—The Stewart High-Economy Enclosed Arc Lamp.

about 97 volts across it as against 75 or 80 volts, in other enclosed arcs. The watts given to the arc itself, and also the mean spherical c.p., are consequently greater.

The Gilbert Arc Lamp.—This lamp, made by the Gilbert Arc Lamp Company, of Chingford, besides being a very prominent one at

the present day, contains some features which are both interesting and instructive. In it the friction of rubbing surfaces is reduced to a very small amount. The upper or $+^{ve}$ carbon-holder and the guide-rod carrying the $-^{ve}$ or lower carbon-holder are attached to a broad copper flexible strap which hangs over a pulley fixed to the top of the lamp. By this arrangement both carbons move towards or away from one another simultaneously, and the arc is therefore maintained always at the same position in the globe. Such an arrangement gives rise to what is termed a *focussing lamp*.

FIG. 216.—General View of Gilbert Arc Lamp (cover removed).

A general view of the working parts of a double-carbon Gilbert open arc lamp is shown in Fig. 216, which is really a duplication of the mechanism of a single arc lamp having one pair of carbons only. The top carbon is clamped in its holder and hangs from one end of the strap, the only guide being a hole in the bottom plate (about an inch above the arc), through which it slides freely. The metal rod carrying the bottom carbon-holder is of rectangular section, and passes just freely through a short length of rectangular tube which acts as its guide and is fixed to the floor and bottom plate of the lamp. The carbons feed together by gravity, the upper holder being heavier than the lower one with its guide-rod. The operation of the lamp is controlled by a simple form of clutch acting directly on the negative carbon guide-rod, and which is in turn controlled by powerful solenoids seen in Fig. 216.

The form of clutch employed is shown in side elevation in Fig. 217, and consists of a rocker-arm E, capable of turning in a vertical plane, on a spindle S passing through its mid-point and carried by the upright support G fixed to the floor F of the lamp-box. To one end of E is attached the movable U-shaped cores of two powerful solenoids, seen in Fig. 216; to the other end, the air dash-pot or damper. One end of the clutch D is supported by a driving-link M from the rocker E, while the other end is held up against an adjustable set-stop C on the pillar P by means of a light spring not shown. The main tube B of the lamp contains the upper carbon, while A is

the rectangular negative guide-rod, which is free to move up or down through the rectangular slide H, except when gripped by the clutch D and pushed downwards. The clutch D is provided with a wearing face K, which is adjustable by means of a set-screw N.

The Action is as follows: After the current is switched off from the lamp, the rocker E (with its attached cores) assumes the position shown in Fig. 217, while the rod A, released from the clutch in virtue of this, becoming horizontal, gravitates freely through the rectangular hole in D, thus bringing the carbons into contact with one another.

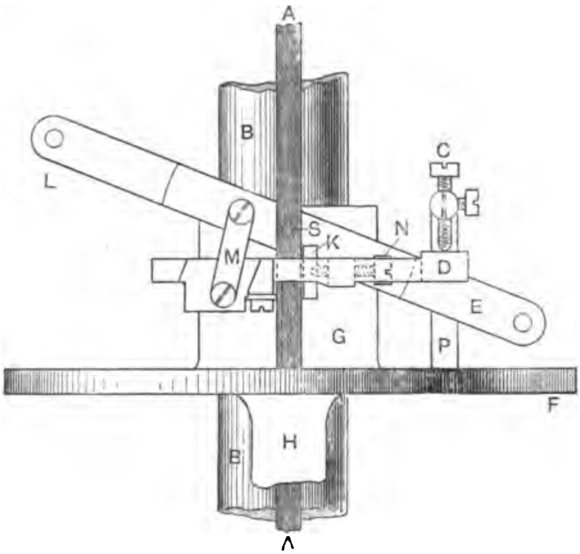


FIG. 217.—Clutch of the Gilbert Arc Lamp.

On switching on, the cores are attracted up into their solenoids (not seen in Fig. 217), E being pulled by them in a counter-clockwise direction. This causes the link M to depress the left-hand end of the clutch D, which binding on A pushes it downwards, thus separating the carbons and striking the arc. The lamp shown in Fig. 216 having two pairs of carbons has also two separate clutches (one at each side), which are worked simultaneously by the solenoids, as seen. The exceptionally powerful solenoids used, combined with the above clutch, make the 'feed' of the carbons very delicate and gradual.

Further, since a clutch requires so little force to make it grip and to actuate it, the makers affirm that these lamps strike to within 15 per cent of their normal working current as against from 50 per cent to 100 per cent in most other lamps. This, of course, reduces the starting current and causes the arc to very quickly assume its normal

condition and maintain it against the tendency of other lamps in series to cause variations. The clutch, moreover, holds the rod A against both ordinary mechanical vibrations and also those due to the reversal of current in alternating systems of supply, even when this is as low as 25 periods per second.

The Gilbert arc lamp, intended for burning from 50 to 80 hours with new carbons, uses four 18-in. carbons in two pairs, each pair extending for almost the whole length of the lamp. The long length of carbons (6 feet) which it is possible to use in this lamp enables, if necessary, a lower or $-^{re}$ carbon of smaller diameter than usual to be used, with a corresponding increase in the optical efficiency of the lamp. A 20-in. spherical or oval globe is used on the 6-ft. carbon lamps, and a 15½-in. globe on lamps using a 12-in. bottom carbon. The makers claim an illumination with alternating currents almost equal in colour to that with direct currents, and with 40 to 43 volts across the arc; and recommend the use of special transformers (ranging from 450 to 700 watts output, according to the lamp used), to which the lamps are connected singly or in a series.

The Gilbert Arc Lamp Company have a special series system, complete with lamps and constant-current moving-coil transformer, which is in use at Eastbourne, Harrogate, etc. In this the lamps are specially arranged so that their regulation is independent of the main current, the same voltage always being maintained across the arcs. The special moving-coil transformers employed can be kept anywhere without needing any attention for months, and replace the earlier system of series lamps with 'reactance or choking' coils across their terminals, which have a low efficiency and 'power factor.'

'Excello' Intense-Flame Arc Lamp.—This lamp, which is made by the Union Electric Company, of London, is probably one of the most important and interesting developments of the present day in arc lamps. Its design presents several novel features, besides showing the beneficial results which, not only in this, but also in every other subject, are obtained by a thorough knowledge and proper application of the *fundamental scientific principles* of the subject. The reader will at once recognise the truth of this when he compares the statements on page 347 with the following description of the above lamp.

The construction and principle involved will be understood from a reference to Fig. 218, which is a diagrammatic view of the chief parts and electrical connections of the latest form of the lamp. It consists of three compartments: a small top one containing the regulating mechanism; the long intermediate one containing an electro-magnet, the stays, carbons, and their guide-rods; and the

bottom compartment consisting of the globe containing the arc at the top of it. The lamp is differentially wound, and the regulating mechanism comprises a fine-wire, potential, or shunt-wound electro-magnet A, connected across the supply mains C C and having the peculiar-shaped pole-piece B. This pole-piece is capable of attracting two soft-iron armatures: one, D, carried at the end of one arm E of a three-limbed casting which is pivoted at a fulcrum F; the other, G, carried at the end of a switch-lever which is pivoted at H. A thick-wire series-wound electro-magnet I, connected in series with the mains and arc, is also capable of attracting the armature D. The carbon-holders, which are made extra heavy, are supported by chains J wound round the last wheel of a train of spur-wheel reduction-gearing K. The motion of this train is controlled by a four-armed fly-wheel L, which is engaged by a detent O carried by the second arm of the three-limbed casting. The third arm of this carries some balance-weights W. The carbons P P, which are simply held by friction in the holders when pushed home into them, feed when the holders are free to gravitate, by reason of their weight, down their slanting guide-rods. This of course can only take place when the detent O releases the four-armed fly-wheel L, so enabling the train of reduction-gear K to rotate. The point of contact of the carbon tips is a little below the under surface of a fireclay cap Q, termed the economiser, which serves a threefold purpose, namely: (1) It acts as a miniature reverberatory furnace or regenerator, retain-

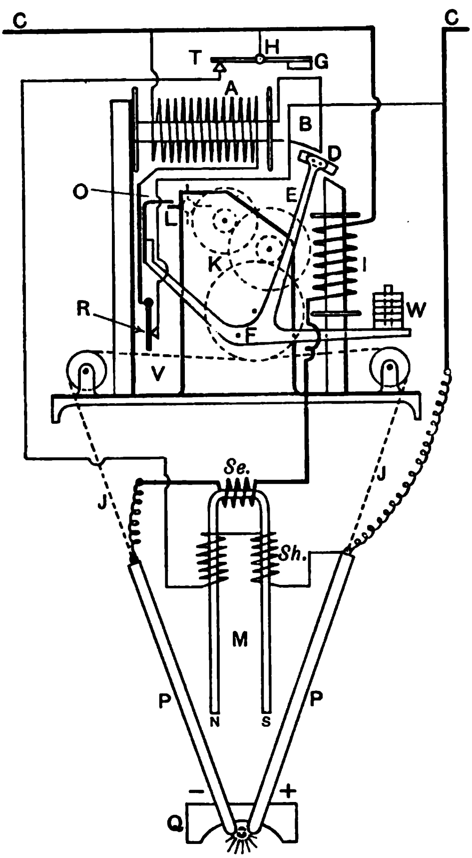


FIG. 218.—Diagram of Excello Arc Lamp.

ing a large quantity of the heat of the arc, which causes this latter

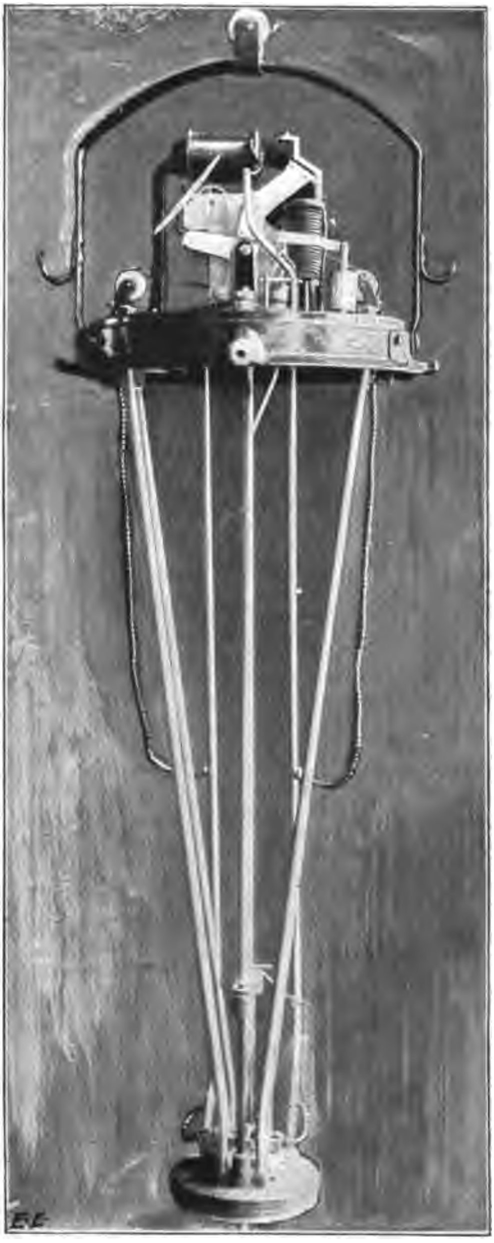


FIG. 219.—Top and Intermediate Chambers of Excello Arc Lamp.

to burn at a higher temperature and prevents the carbon vapour

cooling; (2) it acts as a reflector, throwing down a large proportion of the light, which would otherwise be wasted above the level of the arc; (3) owing to the increased temperature and to the unusually long arc (normally about $\frac{5}{8}$ in. in length), the quantity of carbon consumed per B.O.T. unit is much greater than in an ordinary type arc for the same current. Thus it is that the economiser action of Q comes in, in preventing the influx of too much oxygen. For the above reasons, the position of the arc within the economiser Q is of considerable importance, and a small adjusting-screw in the lamp enables this to be determined with great nicety. Moreover, as both carbons feed towards the arc, this will always retain the same position relatively to the economiser Q, provided the carbons are of the proper relative diameters. A photograph of the working parts or contents of the top and intermediate chambers is shown in Fig. 219. The carbon-guides are those rods which converge from the floor of the mechanism or top chamber down to the economiser-hòlder. The electrical connections between mechanism and carbons are made through the insulated flexible wire, covered with glass beads, as seen in Fig. 219. The lower portions of the lamp, including the floor of the intermediate chamber, which acts as a holder for the economiser (seen underneath), are shown in Figs. 220 and 221.

Action of the Lamp.—The lamp is so arranged that the weight of the carbon-holders always pulls the mechanism into such a position that, when no current flows, the carbons come into contact. When current is switched on to the lamp, the armature D is attracted by the series magnet I and turns clockwise, with the result that the wheel-work acts so as to slightly separate the carbons P P, Fig. 218. At the same time a slider magnetically connected to the gear-work separates them still farther to the required distance, and in this way the arc is struck. The electro-blast magnet M is now energised by the current, and the magnetic field created at its poles N S affects the current through the arc electro-dynamically in the well-known way, repelling the arc downwards and maintaining it across the carbon ends.

As the carbons burn away, the length of arc, and hence the P.D. across it, increases, the result being that the series magnet I becomes weaker, owing to the increase in the resistance of the arc diminishing the current; and the shunt magnet A, having a preponderating influence on the armature D, attracts and causes it to turn counter-clockwise. The detent O is thus caused to release the four-armed fly-wheel L, which makes a quarter of a turn, permitting the carbons to feed by a very small amount corresponding to this motion of L. The armature

D at once returns to its original position of magnetic equilibrium between the poles of A and I corresponding to the correct length of arc. The length of arc is determined, as nearly as can be, by the design of the magnets which balance D at the proper position. This position is determined finally by applying weights in the form of thin zinc washers W, which are firmly secured and provided with permanent interchangeable adjustment.

Fig. 220.—Lower Portions of Excello Lamp, showing Economiser.

The light from this arc is very evenly diffused over practically the whole of the hemisphere below its level — an important feature which distinguishes this lamp from all other arc lamps. This 'even diffusion' is due partly to the downward spreading effect on the arc of the blast magnet, and partly to the curious fact that a crater is formed in the negative as well as in the positive carbon, in consequence of which practically the whole globe is equally and intensely illuminated. This, and the absence of all shadows, give to the lamp a fire-ball effect. When arc lamps containing shunt coils are run in series across circuits of more than 100 volts, considerable heating strain is thrown upon the shunt coils when the carbons burn out. This is provided for in the Excello lamp and other types of lamps of this make by a special winding of the shunt coil, which makes it immune against a voltage as high as 240.

Fig. 221.—Lower Portions of Excello Lamp, showing Economiser.

Again, another contingency, not possible in other arc lamps, has had to be provided for in this lamp, owing to the proximity of the carbons to one another, namely, the possibility of the arc travelling upwards into the lamp when the carbons burn out, and therefore cannot feed any farther downwards. This cannot be entirely met by a series winding on the blast magnet, seeing that if this was strong enough the arc would normally be too much deformed and be liable to extinction with variations of line voltage. The contingency is met as follows: The blast magnet M is provided with an auxiliary shunt winding which is not energised so long as the lamp is working, for its circuit is kept open by reason of B attracting G down and thus keeping the switch-contact T open. When, however, the carbons burn out, a stop V on the feeding-chain automatically opens the contact-switch R, and hence the circuit of the shunt-feeding magnet A. B at once becomes demagnetised, releasing D, which moves instantly over to I, H drawing the carbons far apart. Simultaneously T is closed, the shunt coils of M greatly increasing its magnetic strength, and the arc is promptly blown out.

The carbons used in this lamp are specially long ones to cope with their more rapid rate of consumption, and contain a special core of mineral salts which imbues the light with a pleasant pale golden or yellowish-white colour. This gives the lamp a high fog-penetrative power. Now owing to the length of carbons and presence of the core, coupled with the comparatively small section of carbon and the possibility of the core dropping out from the carbon on account of their different coefficients of expansion with heat, the lamp- and therefore the line-resistance would vary considerably. This in turn would vary the length of arc, intensity of the light, and the lineal rate of consumption of carbon. To prevent this a metal core, seen in Fig. 222, burning away with the carbons, is introduced with the salts in such a way that there is a permanent spring-contact at about every ½ in. along the carbon. This not only plays an important part in the regular burning of the lamp, but produces a low-resistance carbon in which there is extremely little loss of pressure. The carbons in the first batch of lamps made were each 30 ins. long, and together absorbed about 18 volts, so that the special ones now used are a great improvement.

To prevent the products of combustion affecting the mechanism, both the top and intermediate chambers are made with close-fitting hoods and are nearly air-tight. For draughty situations, the arc can be enclosed in an inner combustion-chamber which only slightly reduces the c.p. while greatly protecting the arc from rapid burning.

The 'Excello' lamp is made in two sizes, *e* and *f*, for both direct and alternating current, and in four rated current capacities to each size. All are differentially wound, can be used in single parallel or in long series up to 1000 volts or more, and will only work with their rated current.

Direct-current lamps range from 6 to 12 amperes at from 44 to 47 volts respectively across their terminals, and will burn two in series on 110, 3 in series on 160, and 4 in series on 220 to 240 volts. Size *e* uses two carbons each 15¾ ins. long; diameters—positive 8 to 11 mm., negative 7 to 10 mm.; and burning 9 to 10½ hours respectively in the ratings 6 to 12 amperes. Size *f* uses 23½-in. carbons, burning 15½ to 17½ hours.

Alternating-current lamps range from 8 to 15 amperes at 44 to 47 volts, and have carbons as above, but 7 to 10 mm. diameter. The

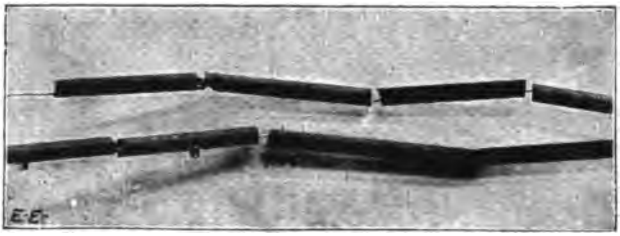


FIG. 222.—Broken Excello Carbon showing Metallic Core.

burning hours are about 10 per cent greater than with direct currents while a line voltage of 55 for a single lamp, and 110 volts for two in series, is needed.

The candle-power of this lamp, as in every other type, depends on the current through the arc, and whether the current is direct or alternating. The c.p. in every lamp, moreover, varies greatly in different directions; the most useful direction, except in so-called inverted arc lamps, being from the lower hemisphere concentric with the arc.

Now the c.p. of an arc lamp can be measured in a large number of different directions, making known angles with one another, in a vertical plane. If, therefore, a linear scale of c.p. (*e.g.* so many candles per inch or per cm.) be chosen, a number of lines, radiating from the arc as a centre, can be drawn so that their length represents the c.p. in that direction. On joining the extremities of these lines a curve is obtained known as the 'polar curve' of distribution of light from the arc. Such a curve is shown in Fig. 223 for a 10-ampere Excello direct-current arc lamp; and if a mean of all the various c.p.'s in different directions in the vertical plane be taken, a semicircle can be drawn, with

2 B

the arc as centre, at a radius corresponding to this mean c.p. Repeating the above for a number of other vertical planes, and taking the mean of all the respective means for the different planes, we obtain what is called the *mean hemispherical c.p.* of the arc.

The distribution[1] shown in Fig. 223 is that on the right of a vertical line through the arc, and would be repeated on the other side of this

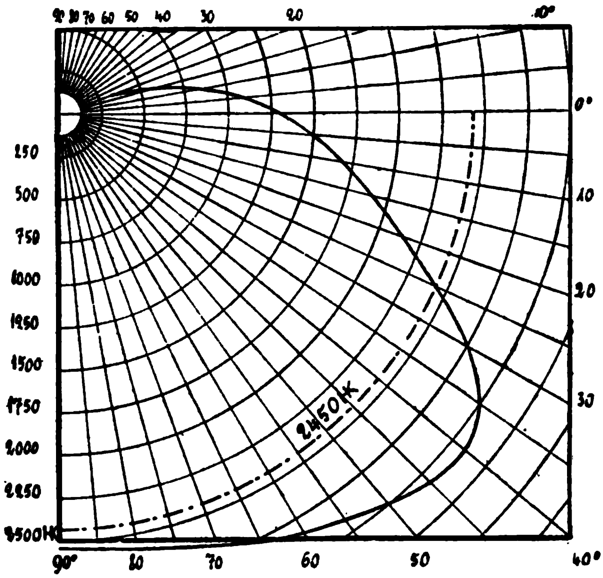


FIG. 223.—Polar Curve of Distribution of C.P. from a 10-Ampere Excello Direct-Current Arc Lamp.

line, which is an axis of symmetry as well as a scale of c.p. As seen, the mean hemispherical c.p. is 2450, while the maximum c.p. emitted, at an angle of forty degrees to the horizontal, is 3100.

The following table shows the mean hemispherical c.p. given by the various stock current ratings of Excello lamps for alternating and direct current :—

[1] This is well set forth in an article on 'Radiation from Intensive Arc Lamps,' by B. Monasch, *Elektro. Zeitschr.* 26. pp. 67-72, January 19, 1905.

[TABLE

TABLE XIV

Current.	Mean Hemispherical Candle-Power with Direct Current.	Mean Hemispherical Candle-Power with Alternating Current.
6	1300	
8	1800	1500
10	2450	2000
12	3780	2750
15	...	4000

From these figures we see that the c.p. increases more rapidly than the current, whether this be direct or alternating. A most important characteristic of this lamp is its high optical efficiency, or the ratio of the c.p. to the energy absorbed.

The following figures[1] enable a very interesting comparison to be drawn between the illuminating power of this lamp and that of the ordinary *open* and the *enclosed* types (direct current):—

TABLE XV

Flame Arc Lamp Efficiency.			Open Arc Lamp.			Enclosed Arc Lamp (inner cylinder only).		
Watts.	M.H. C.P.	C.P. Watts.	Watts.	M.H. C.P.	C.P. Watts.	Watts.	M.H. C.P.	C.P. Watts.
300	1320	4·40	287	610	2·12	300	330	1·10
387	1700	4·40	400	895	2·24	400	520	1·30
515	2125	4·12	503	1365	2·06	510	710	1·39

Thus we see that, so far as these tests go, the efficiency of the flame lamp is twice that of the open type and four times that of the enclosed, which is also indicated in Fig. 224, while the c.p. is also much greater for the same consumption of power.

In addition to the above, there are other flame arc lamps, *e.g.* that with *adjacent parallel carbons*, made by Messrs. Siemens and Halske (*Schweizerische Blätter für Elektrotechnik*, 8. p. 178, December 8, 1903). Lamps in which a diffuser (p. 372) is used are also a departure in practically the same direction.

In the Bremer arc lamp,[2] which possesses some important characteristics, the carbons are arranged horizontally, and the arc

[1] *The Electrical Review*, March 28 and April 11, 1902.

[2] *Elektro. Zeitschr.* 21. pp. 546-549, July 1900, and *Deutsch. phys. Gesell.* Verh. 5, 7, pp. 157-175, April 15, 1903.

is deflected downwards by electro-magnetic means. The advantages claimed are: improved distribution of light; an efficiency two or three times that of ordinary arcs; and, lastly, a light of better colour owing to the carbons being impregnated with compounds of calcium, etc.

Arc-Light Diffusers.—The efficiency of any arc lamp can be greatly improved, and, according to recent tests, the c.p. nearly doubled, by attaching to it the specially prepared Bonhivers diffuser, consisting of refractory earth discs baked at very high temperature and

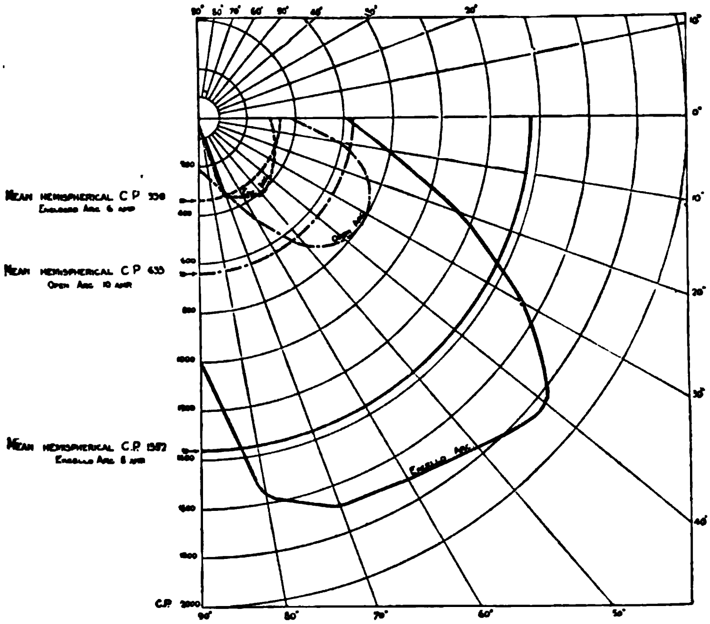


FIG. 224.—Polar Curves of Enclosed, Open, and Excello Arc Lamps.

With current at 4d. per unit the cost of 1000 candle-power of light per hour is:—
With Enclosed Arc Lamp, $5\frac{3}{4}$d.; with Open Arc Lamp, $3\frac{1}{16}$d.; with Excello Arc Lamp, $1\frac{3}{5}$d.

impregnated with oxides of the rare earth metals. The discs can be either concave, plane, or convex: from 8 to 10 mm. thick, and from 65 to 125 mm. diameter. For direct-current lamps, the bottom carbon is made the $+^{ve}$, and the arc arranged to be from 6 to 12 mm. below the diffuser, according to the current used in the lamp. The light and heat emitted from the arc is sent up to the diffuser, which, becoming incandescent, reflects it down again; the rays emitted, from the disc absorbing the violet and red rays from the arc, causing an illumination resembling *sunlight.* The life of the diffuser is estimated at about 2000 hours.

Electrolytic Arc Lamp.—This is a new form of arc lamp introduced by E. Rasch,[1] in which are used electrodes of magnesia, lime, thoria, zirconia, or other highly refractory substances. The efficiency of the arc with such electrodes is greater than with ordinary carbon ones, but, being bad conductors (cold), they have to be heated by a subsidiary arc to start the main arc and make them conductors. The efficiency is said to be from 0·25 to 0·35 watts per candle.

The Magnetite Arc Lamp.—This lamp, so called from the black oxide of iron, *magnetite*, being used as an electrode in the lamp, has been developed by The General Electric Company of America. The +[ve] electrode, ½ in. to ⅝ in. in diameter, consists of a copper segment, of such a size that it does not get too hot and therefore does not wear away. The −[ve] electrode consists of magnetite, compressed, in the form of an impalpable powder, within a thin iron tube. As the lamp burns, the +[ve] or copper electrode, forming a permanent part of the lamp, becomes hot enough to avoid the deposition on it of the material of the −[ve] electrode, *i.e.* of fused globules of magnetite. None of the light comes from the +[ve], it being emitted from the column of vapour, which is from ¾ in. to 1⅛ in. long. Of the various oxides, *magnetite* is the best, because it is a good conductor, is stable at all temperatures, very plentiful in nature, and gives a white arc of high efficiency,

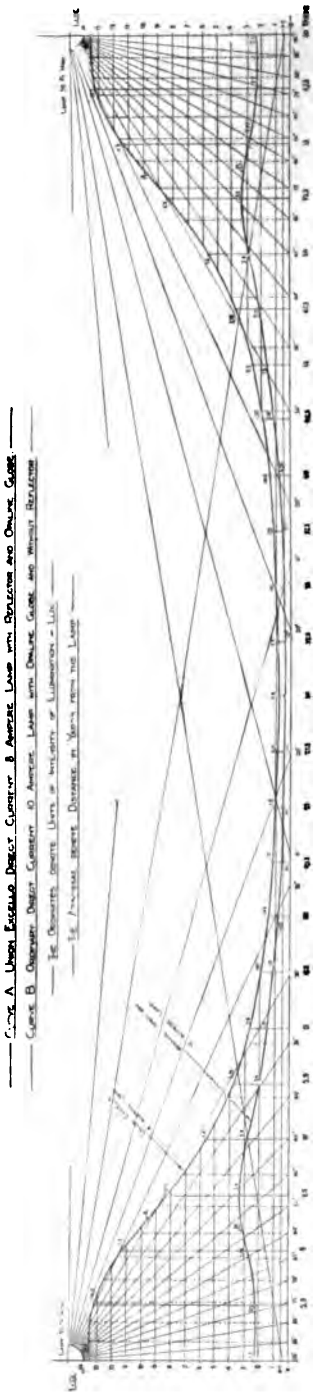


FIG. 225.—Distribution of Illumination from Ordinary and Excello Arc Lamps.

[1] *Elektro. Zeitschr.* 22. pp. 153-157, Feb. 14, 1901.

about twice that of the ordinary carbon arc. It burns at the rate of only about $\frac{1}{8}$ in. per hour, which is reduced by the addition of other substances, such as titanium compounds. The lamp takes about 4 amperes at 80 volts, and with electrodes $\frac{1}{2}$ in. diameter burns for 100 hours, or with $\frac{5}{8}$-in. diameter electrodes it burns for 200 hours. The fine smoke given off is conveyed away by a chimney, and a nickel reflector inside the globe adds some 10 per cent to the illumination.

Foster Hot-Wire-Control Arc Lamp.—Probably foremost in the enterprising attempts to simplify arc-lamp mechanism is that embodying the application of the thermal property of an electric current. The principle involved and object to be attained are, of course, the control of the arc by means of the heating and consequent expansion of a wire or strip, due to the passage through it of the current supplied to the lamp. Various attempts have been made, of recent years, to solve the problem, but without commercial success, until Mr. C. E. Foster, in 1901, devised the lamp which he has recently perfected and placed on the market. This lamp eliminates the dash-pot or damper, and either the electro-magnet or solenoid with its plunger, inseparable from the mechanism of every other type of arc lamp. Many of the inherent troubles common to arc lamps in the past therefore disappear or are reduced to a minimum; for such, when they do occur, are mainly caused by the damper sticking, through dust and dirt, or the coil burning out.

Before reviewing the merits, or otherwise, of the lamp, it may be well to give a description of its construction, so that the reader may better appreciate the various points. A complete sectional elevation of the lamp, with case removed, is shown in Fig. 226, from which it will be seen that the lower carbon is fixed, while the upper one is actuated on the *clutch* principle. The two cables from the source of supply are connected respectively to the two terminals marked + and − which are carried by, but insulated from, the top cap of the lamp. This top also carries the shackle insulator for supporting the whole lamp, as well as the tubular centre-post P, which in turn carries the remainder of the lamp. The + terminal is electrically connected by an insulated wire S to a metal block V fixed to, but insulated from, the floor of the lamp-case. Two metal expansion strips R R terminating in stirrups N N hang from the opposite hooked ends of a bar M, their lower ends being attached to V and the hook T respectively. The bar M can oscillate on a fulcrum carried by the screwed rod L, which, though insulated from the case, can be raised or lowered by turning the nut K. The tension of the strips R R can

therefore be altered, and the feed of the carbons consequently adjusted faster or slower. The strips are also connected electrically at their upper ends by the wire shown, in order to avoid any sparking at M. The bar terminating in the hook T is carried by a rigid rod B, pivoted at its upper end, and is not only connected by a link E to a disc F, but also electrically connected by a flexible wire D (insulated with glass beads) to the upper carbon-holder Q, which slides freely in the tube P. On the same axle as the disc F is a crank-arm U, the outer end of which is loosely pinned to the projection W from a flat washer, through which the upper carbon passes freely when the washer is resting on the floor of the case. There is a little play between U and F to enable R R to attain a fairly high temperature before the arc is struck. The upper carbon-holder Q is merely a split tube into which the carbon is pushed home. The lower or $-^{ve}$ carbon is clamped in a fixed holder Y carried by the metal rods H H from the floor of the case, and these are in turn electrically connected by an insulated wire A to the $-^{ve}$ terminal of the lamp. A spring C stretched between the top of the lamp and a pin on the side of F near the rim, always tends to turn F counter-clockwise, and hence maintain R R always taut. A steatite ring G clamped by a screwed bush X guides the upper carbon through

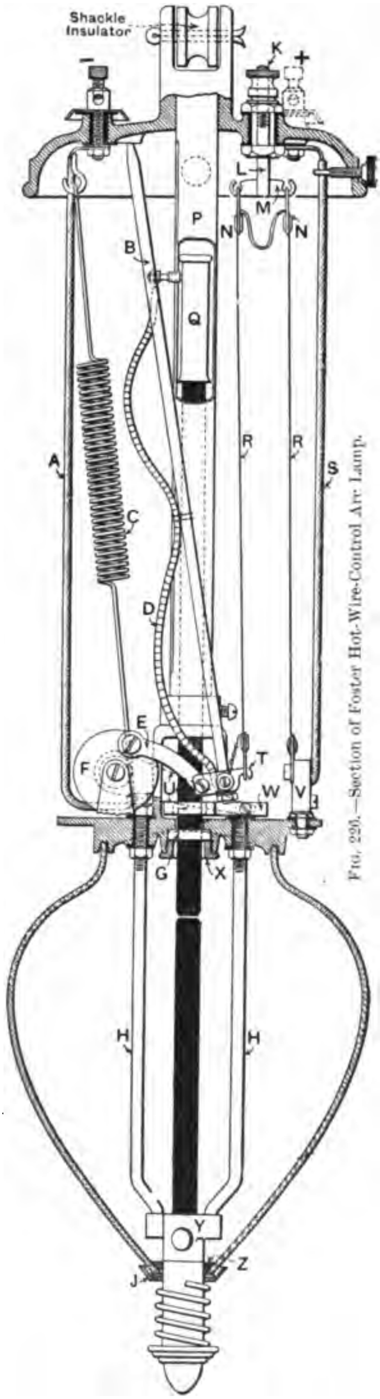


FIG. 223.—Section of Foster Hot-Wire-Control Arc Lamp.

the floor of the case, while the hole in the clutch-ring W is also lined with the same metal. Only one globe is employed, the upper rim of which fits closely into an annular groove in the under side of the floor of the case. The lower end is fitted with a globe dish J and carries a close-fitting washer Z for preventing air leakage, and is pushed upwards by a spring compressed by a nut working on the tail-rod of Y.

Action of Lamp.—For no current flowing, the upper carbon gravitates on to, and comes into contact with, the lower one, sliding through the clutch-ring W, which is horizontal. When, therefore, the current is switched on, the strips R R carrying it expand, and the spring C immediately takes up the slack, causing F to turn counter-clockwise, and W to be tilted so as to bind on the upper carbon. The further motion of F raises W bodily, and with it the upper carbon, until equilibrium is established by the current flowing through R R and a certain length of arc raising R R to a steady temperature. As the carbons consume away, the arc increases in length, while the current and consequent expansion of R R decreases. The clutch-ring W is thereby tilted back more towards the horizontal position, and allows the upper carbon to very gradually and imperceptibly feed or glide through it.

The above lamp is shown one-quarter full size, and, complete, weighs about 12 lbs., while the mechanism weighs about ½ lb. It is made by Messrs. Foster and Co., of Worple Road, Wimbledon, and regulates equally well with either continuous or alternating current without any alteration at all. In fact, these lamps can be switched from a direct- to an alternating-current supply, or *vice versa*, without stopping the arc, thus making it possible for a pure direct-current lighting plant to have an alternating-current stand-by, or *vice versa*, in case of the break-down of the former.

Whilst the ordinary electro-magnetically controlled type of arc lamp can only be run two in series *on alternating pressures* from 220 to 250 volts, the hot-wire lamp can be run three in series without any other resistance in series. Thus 33 per cent more light is obtained in the latter case for the same consumption of energy. The reason of this is that the hot-wire lamp has no self-induction, and therefore introduces no back E.M.F., as do lamps containing electro-magnets. The whole of the supply voltage is therefore effective in operating the lamp, and the product (amperes × volts) represents the true watts absorbed, the so-called *power factor* of the lamp being unity.

The higher the circuit voltage the greater the efficiency of the hot-wire, but the smaller that of the magnet, controlled lamp. In some

recent tests it was shown that three lamps in series on a 240-volt direct-current circuit required no extra resistance. The current was 5·5 amperes, and the total voltage at the terminals of the arcs was 216, or 72 volts per arc, the carbons being solid and the arc quite steady. This result means a production of nearly 50 per cent more light for the same energy absorbed than in the ordinary arc lamp. On 100 to 200 and 220 volts the saving is from 10 to 25 per cent.

The internal resistance of the lamp between terminals is about 2 ohms. In the case of alternating currents, one, two, or three of these lamps can be operated in conjunction with a three-way compensator transformer and so-called choking coil. A recent test of a lamp with this combination showed the current to be 2¼ amperes at 220 volts and 50 periods per second, total consumption 495 watts, of which 58 were in the compensator and choker. When two additional lamps were added to the compensator, the extinction of one of them in no way affected the other two. The three lamps are in series with one another across the 220-volt main, one being in shunt to each of the three sections of the compensator, which is also across the same mains.

The lamp is practically dead-beat in its operation, and with alternating current is nearly noiseless, the usual rhythmic hum common to electro-magnetic lamps being absent.

Owing to friction at the moving parts being reduced to a minimum, the spring C is quite a light one and the tension on the strips R R only a few ounces when hot. They will stand about ten times the tension which C can produce on them without permanent elongation, and will stand safely about three times the current taken in 'striking' the arc. A strip which had been in use for two years elongated about 15 per cent before breaking at 46-lbs. tension. It is estimated that they will last for at least five years, and the cost of a new one only amounts to from two to five shillings.

The lamp is intended to use a $+^{ve}$ or upper carbon 14 ins. long and a $-^{ve}$ 7 ins. long, both *solid*, 13 mm. diameter, for *continuous*, or 10 mm. diameter, *cored*, for *alternating* current. If the arc, which is about ⅜ in. long, tends to flick out through being too long, the head K must be screwed clockwise a little at intervals, until the tension on the strips R R is increased to the right amount to give a steady arc. The reverse must be done if the arc is too short. Equality in the lengths of arc can in this way be obtained in two or more lamps running in series. One trimming of carbons lasts from 40 to 80 hours, according to the size and quality of carbons and to the magnitude and constancy of the voltage.

The lamp for direct current burns direct on 100 to 120 volts, and requires only one external resistance for 120 to 250 volts. For alternating current at 100 to 120 volts an external choker is needed.

Resistances, Choking Coils, and Economy Coils for Arc Lamps.—Some few years ago it was customary to see arc lamps run in one long connected series only, there being as many as sixty-five lamps in series with each other, all taking the same constant current. Owing, however, to the necessity for providing special generating plant for supplying this constant current at so high a voltage (65 × 50, or 3250 volts), although in America 175-light machines are used giving a constant current of 6·5 amperes at 10,500 volts, engineers have turned their attention to the ways and means for running arc lamps either singly or in series of two, three, four, up to ten, across constant-potential mains.

Now suppose that two arc lamps, each requiring 10 amperes at 50 volts, have to be run in series from 110-volt constant-pressure supply mains M M. Then obviously the surplus voltage (10 in this case) must be absorbed independently, and this is done in the case of direct currents by connecting in series with the lamps L_1 L_2 an extra or so-called *line resistance* R as shown in Fig. 227. This is wound with wire of sufficient gauge to carry the lamp current without excessive heating.

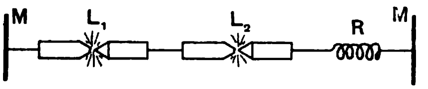


FIG. 227.—Arc Lamps in Series with Line Resistance.

An adjustable line resistance of the double-coil type supplied by the Sun Electrical Company, London, is shown in Fig. 228, with ventilating perforated cover removed. The wire is wound on two cylinders of non-combustible insulating material, such as slate or earthenware. A movable clamp sliding along a contact-rod (seen in the figure) alters the terminal resistance according to its position. This form of resistance is made also with single coils only. In another type, spirals of the wire are wrapped round a hollow insulating frame about 7 ins. diameter by 5½ ins. deep, in the manner shown in Figs. 229 and 230 (without and with cover). The top carries the suspension insulator, and the bottom a hook from which the lamp is hung.

With alternating currents, a *reactance*, *impedance*, *choking coil*, or *choker*, as it is variously termed, is used, in the place of R (Fig. 227), for absorbing the surplus voltage.

Many different forms of choking coil, all effecting the same object, are in use, and, therefore, the general principles of construction and

action will be understood by a description of one form commonly met with and illustrated in Fig. 231. It consists of m-shaped stampings out of soft annealed thin sheet charcoal iron, which are varnished on one face and then assembled side by side (with varnished sides all facing one way) to form a thick or deep m-shaped block. The plates are therefore all insulated from one another by one thickness of varnish, and are clamped tightly together by five long bolts, as shown. Two such laminated m-shaped blocks are clamped face to face on a base, by means of the metal frame at the top and a long vertical bolt on each side, as shown. The central tongues project through opposite ends of a coil, and meet at its centre. The coil is wound with cotton-covered copper wire large enough to carry the lamp current, and is tapped at intervals by wires connected with five terminals carried by and insulated from the base.

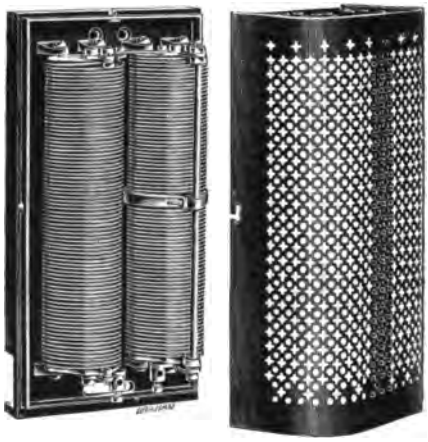


FIG. 228.—Adjustable Line Resistance.

When an alternating current is sent through the choker, and it can only be used with such a current, the lines of magnetic force created all pass through the centre core of the coil, completing their

FIG. 229.—Line Resistance.

FIG. 230.—Line Resistance.

path through both side limbs. From the principles explained on page 194 *et seq.*, a self-induced or back E.M.F. will be created in the coil, which will neutralise an equal portion of the E.M.F. of the source. This back E.M.F. can be diminished by only sending the current through a fewer number of turns in the coil, which can be done if this is wound in sections, the iron core remaining untouched, or by

keeping the same number of turns and inserting non-magnetic *distance-pieces* between the tongues of the two laminated blocks, which decreases the strength of the magnetic field by increasing the resistance of the magnetic circuit (*vide* p. 136). Nearly all chokers have therefore either an adjustable core or coil wound in sections, or both.

FIG. 231.—Choking Coil.

The device R (Fig. 227), whether it be a *line resistance* for direct current or *choking coil* for alternating current, not only absorbs the surplus voltage, but also serves to steady the burning of the lamps, and is therefore sometimes termed a *steadying resistance.*

The reader must also remember that, while the *same amount of energy* is taken from the mains M M, for the same voltage between them and current, the choker wastes less energy in heat than a line resistance with alternating currents, owing to its low metallic resistance and special magnetic circuit. A choking coil can, with advantage, be used as a shunt to the terminals of each lamp when there are two or more in series. For instance, if used with the arrangement shown in Fig. 227, we have that of Fig. 232, where C_1 C_2 are two chokers, and when used in this way they are called *balancing* or *distribution coils.*

The chokers C_1 C_2 are designed so that, although they can carry

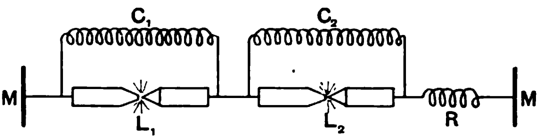


FIG. 232.—Arc Lamps in combination with Balancing Coils and Line Resistance.

the whole lamp current safely, they shunt very little current when the lamp has its *proper* terminal voltage and proper length of arc. Under this latter condition, the specially small cores are designed so as to be nearly magnetically saturated, and therefore, since the back E.M.F. varies directly as the product (turns × flux), an increase of terminal supply voltage affects the flux, and hence the back E.M.F., very little, and the result is an increase of current through the choker.

It will now be seen that if the arc lengthens, the terminal P.D. increases, and the choker passes more current until the arc returns to its normal length. In addition, therefore, to the choker maintaining a more constant P.D. at the lamp terminals, it acts as a *cut-out* and *substitutional resistance* in the event of the carbons being unable to feed, for then the whole current passes through it, and its back E.M.F. replaces that originally required at the lamp terminals. The remaining lamps of the series therefore go on burning properly just the same.

When the supply voltage is *very much* in excess of that required for one or a given number of alternating-current arc lamps, it is more economical and convenient to run them from a so-called *compensator* or *economy coil*. This is practically a combination of a choking coil and transformer, and of course can only be used with alternating currents. The principle will be understood by a reference to the diagram, Fig. 233, in which M M are the supply mains at, say, 110 volts, L a lamp requiring, say, 10 amperes at 50 volts, and P S the compensator. The thick and thin wire coils P and S are wound on a well-laminated closed magnetic circuit, and together constitute a transformer, while P alone acts as a choking coil to L and S.

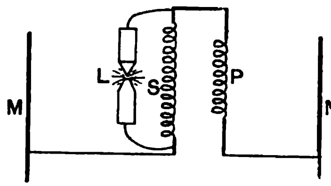


FIG. 233.—Principle of Economy Coil.

Now it will be seen that the current in P flows through L, and by transformer action induces in S the E.M.F. of 50 volts required for the lamp. This secondary E.M.F. in S causes the remainder of the current required for L to flow through it. In the present instance the economy coils or their core would be adjusted so that 5 amperes flowed through P and L, and the E.M.F. of S added a further 5 amperes to that through L, making the necessary 10 amperes at 50 volts (or 500 watts). Further, it will be seen that only 5 × 110, or 550 watts, are taken from M M as against double this if the arrangement of Fig. 227 had been used.

A saving is effected in the running cost of at least 70 or 80 per cent by using a compensator instead of a choker. Two lamps can be worked off the same compensator by connecting the second lamp across the terminals of P. In this case the two lamps can be worked quite independently of one another, and when both are burning they are in series. Should one go out, the other continues to burn with economy (*vide* p. 380). The device obviates the necessity of protecting the shunt coils of arc lamps, and is made to transform in the ratio of 4 to 1 for 200-volt and from 2 to 1 for 100-volt circuits. Further,

the choking effect can be adjusted to suit any current and periodicity of the alternating current.

We may now with advantage mention some important points relating to the illumination derived from arc lamps in general. The candle-power (c.p.) of such lamps depends upon the current, voltage, length of arc, quality and diameter of carbons, enclosing globe, and nature of current, whether direct current (D.C.) or alternating (A.C.), and the position of the arc in the globe. With so many dependencies, makers of arc lamps have given up even mentioning candle-power, and content themselves by rating their lamps on the current and voltage required. The c.p. does, however, range from about 150 in the midget types (taking $1\frac{1}{2}$ ampere at about 65 volts, *i.e.* 97 watts) to over 3000 c.p. in some of the 'open' types (taking 12 amperes at 55 volts, *i.e.* 660 watts) with globe or globes complete.

The globe, however, absorbs a large percentage of the light emitted from the arc itself, but on the other hand helps to diffuse it more uniformly in space. From photometric tests on the absorption of light by globes of different kinds of glass used for the purpose, we find it to be about 8 per cent for clear glass; 11 per cent for holoplane glass; 30 per cent for light ground glass; 40 to 50 per cent for heavy ground glass; and 50 to 70 per cent for strong opal glass. It has been proved experimentally that the best results are obtained with the arc at the centre of the globe. The optical efficiency of the naked arc is therefore usually much greater than that of the lamp with globe, the latter ranging from about $\frac{1}{6}$ to 2 watts per mean spherical candle-power (see p. 370), according to the type of lamp used. It is from 10 to 30 per cent greater with D.C. than with alternating currents, and is some 75 per cent greater in 'open' type arc lamps than in the 'enclosed' type used with D.C.

It is interesting to compare both the *intensity* and *distribution* of illumination in the case of open and enclosed arc lamps. Some time ago careful tests of c.p. at various angles were made on a number of different makes of *open* arc lamps with globes. These may now be compared with similar tests on a Jandus *enclosed* arc lamp, with clear inner and outer globes, and run from 110-volt mains with 80 volts across the arc and an average current of 5·6 amperes through it. The maximum c.p. was found to be 1295, but the results for the 'enclosed' and the mean of those for the 'open' arc tests are both reduced in proportion, with a maximum of 1000, and plotted in Figs. 234 and 235. The carbons and lengths of arcs are drawn to scale in both cases. The latter, it will be seen, is a controlling factor in determining not only the angle of maximum c.p., but also its range in

a vertical plane. The *maximum rays* from the *long* or *enclosed* arc lamp (Fig. 234), from their greater elevation, strike the ground at nearly twice the distance from the lamp that those from the open arc type do, while being more evenly distributed. The relative forms in which the carbons burn away are well illustrated in Figs. 234 and 235. The burning hours are increased by decreasing the size of the combustion globe of the enclosed lamp, but for the usual size the consumption of carbon is about 0·05 in. per hour for the + ve, and 0·025 in. per hour

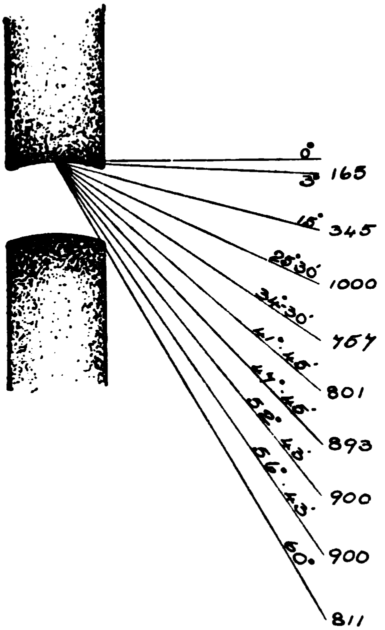


FIG. 234.—Enclosed Arc.

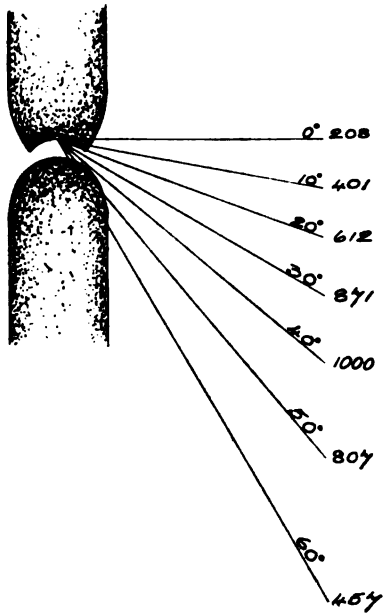


FIG. 235.—Open Arc.

for the – ve carbon. With alternating-current enclosed arc lamps the rate of consumption of carbon is about 0·06 in. per hour.

Variation of C.P. with Diameter of Carbon.—This is well shown by the results of some tests on a lamp, taking $3\frac{1}{2}$ amperes at 80 volts, by G. N. Eastman.[1] For example, using carbons of various diameters, and measuring the c.p. always in the same direction, the following results were obtained:—

Diam.—	$\frac{1}{2}$	$\frac{7}{16}$	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{1}{4}$	$\frac{3}{16}$	$\frac{1}{8}$
C.P.—	196	322	351	394	378	485	554

These figures show that the c.p. and efficiency increase as the diameter of carbons used decreases, for the same amount of electrical energy absorbed.

[1] *Elect. World and Engin.* 45. pp. 722, 723, April 15, 1905.

QUESTIONS ON CHAPTER IX

[*Supplement all Answers with Sketches when possible.*]

1. Why are glow-lamps generally arranged in parallel, while arc lamps are frequently joined in series? (Prelim. C. and G. 1897.)

2. Give sketches describing the best known arc-lamp mechanisms, and state which type you would prefer to employ on a constant-pressure circuit. Give full reasons. (Hons. Sect. II. C. and G. 1897.)

3. Draw polar curves showing the distribution of light with an open direct- and with an open alternating-current arc; also with an enclosed direct-current arc. From these, estimate the total amounts of light that are sent out downwards within a cone, the generating lines of which make an angle of forty-five degrees with a vertical line through the arc. (Hons. Sect. II. C. and G. 1898.)

4. A single arc lamp is supplied with current from a pair of mains at a pressure of 100 volts. What other apparatus is necessary, in addition to the lamp itself, (*a*) when the current is direct, (*b*) when it is alternating? (Prelim. C. and G. 1899.)

5. Sketch and describe some form of enclosed arc lamp, and mention the chief points in which its working differs from that of an open arc lamp. Under what circumstances will the open arc type be the more economical to employ? (Hons. Sect. II. C. and G. 1899.)

6. What are the important differences between an arc lamp intended for use on a series circuit and one employed on a parallel circuit? Explain the reason for each of the differences. (Ord. C. and G. 1900.)

7. Two arc lamps are supplied from different sources, one alternating, the other direct current; the current, indicated by suitable instruments, is 10 amperes and the pressure 100 volts in each case. On the direct-current circuit the voltage on the lamp terminals is reduced by 45 by means of a resistance coil, and on the alternating-current circuit by an impedence coil. Explain why, although the current and voltage of the two lamp circuits is the same, the direct-current one will consume nearly twice as much energy as the alternating-current lamp circuit. (Hons. Sect. II. C. and G. 1900.)

8. Describe, with sketches, the striking and regulating mechanism of some good form of arc lamp. (Prelim. C. and G. 1901.)

9. Why, by the expenditure of the same amount of power, is so much more light produced with an arc than with a glow lamp? (Prelim. C. and G. 1901.)

10. Discuss the relative merits and demerits of open and enclosed arc lamps when run from a 240 direct-current circuit. (Prelim. C. and G. 1901.)

11. Describe shortly, with sketches of the regulating mechanism, the best form of arc lamp with which you are acquainted, and call attention to any points which you consider specially good. (Ord. C. and G. 1902.)

12. Describe accurately, but in as few words as possible, any good form of arc lamp with which you are familiar, making clear sketches of essential parts. (Ord. C. and G. 1904.)

CHAPTER X

THE PRODUCTION OF ELECTRO-MOTIVE FORCE (THERMO-GENERATORS —PRIMARY CELLS—SECONDARY CELLS)

The Production of E.M.F. Thermally.—If the junction or point of contact between the ends of two bars or rods, composed of *different* metals, is heated, an E.M.F. is set up between the free ends of the bars, so long as a *difference of temperature* exists between the junction and these ends. If, then, these are connected by a conductor, the E.M.F. will cause a current to flow in the closed circuit so formed. The E.M.F., and therefore also the current, will be constant as long as the temperature conditions are constant. This phenomenon was discovered by Seebeck, of Berlin, as far back as 1821-2, and is observable with any two *different* metals. It is all the more interesting, and even fascinating, on account of the direct transformation of heat into electrical energy.

The arrangement mentioned above is known as a *thermo-couple*, and is illustrated diagrammatically in Fig. 236; A and B being the metal bars, J their heated junction, and C the outside circuit connection. If the bars A and B are of *antimony* and *bismuth* respectively, then, if the junction J is *heated* to a higher temperature than the remainder of the bars, a current will flow in the direction of the arrows. This is easily remembered from the fact that the current flows from Antimony to Bismuth through a Cold junction, and the letters A, B, C. If J is *cooled* to a lower temperature than the remainder of the bars, the *current* will just be *reversed* in direction.

A metal is said to be thermo-electrically $+^{ve}$ to another when the E.M.F. which they set up tends to send a current from the *first to the second through the hot junction.* Thus bismuth is $+^{ve}$ and antimony $-^{ve}$ at the junction J (Fig. 236), and it will be noticed that this distinction of sign is in agreement with that met with in the electro-chemical series of substances (p. 392), namely, any substance is electro-chemically $+^{ve}$ to another when the E.M.F. set up by them

tends to send a current from the *first to the second through the liquid of the voltaic cell.*

Now the thermo-electric property varies with every pair of different metals very considerably in many cases, being greatly affected by the presence of impurities, while their relative signs are, in some cases, even reversed at different temperatures. This last-named phenomenon is perhaps most easily exhibited with a copper-iron thermo-couple, on account of the necessary range of temperature being smaller with such. Suppose, therefore, that the twisted junction of a copper and an iron wire can be heated gradually to any desired extent, and a very sensitive high-resistance voltmeter be applied to the free ends, which remain at the temperature of the room. Then, as the temperature *increases continuously*, the E.M.F. of the couple (which is given by the voltmeter reading) increases to a maximum, then decreases to zero, and reverses sign afterward, finally increasing again in the opposite sense to what it did before.

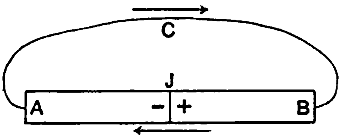


FIG. 236.—Principle of a Thermo-couple.

It can also be shown that the maximum E.M.F. is always attained at the same temperature, which is called the *neutral point* of that couple, no matter what the temperature of the rest of the circuit may be. Further, the temperature of reversal (TR) is as much above that of maximum E.M.F. (TME) as this latter is above the temperature of the cool junction (TCJ). In other words, the temperature of maximum E.M.F. is midway between the temperatures of reversal and of the cool junction, or

$$T_{ME} = \frac{T_R + T_{CJ}}{2}.$$

If C, in Fig. 236, is a copper wire, say, the thermo-E.M.F. at the junction of C and B opposes that at J, and also the E.M.F. at the junction of A and C; but since the *thermo-electric effect of any element of a circuit is zero if the extremities of that element are at the same temperature*, it follows that when the ends of C are at the same temperature the E.M.F. at J is the only one acting in the circuit.

Laws of Thermo-E.M.F.'s.—These at once follow from the above remarks, and may be stated thus:—

1. The thermo-E.M.F. of any pair of substances is roughly proportional to the excess of temperature of their junction over the remainder of the circuit within a given range of temperature.

2. The total or effective thermo-E.M.F. acting in a compound circuit composed of conductors of different materials is equal to the

algebraical sum of all the separate thermo-E.M.F.'s at the various junctions.

Source of Thermo-E.M.F.: Peltier and Thomson Effects.—Peltier in 1834 discovered that the junction of a thermo-couple becomes hotter when a current from some outside source is sent through it in one direction, than when the same current is sent in the opposite direction. This means that one junction is heated by the absorption of heat at it, the other cooled by heat being evolved from it. Further, the cooled junction, if heated, produces a thermo-current in the same direction as that which heated it; or, in other words, the junction J (Fig. 236) would be cooled by a current from an outside source flowing from B to A. From this it is seen that the Peltier and Seebeck effects are the converse of one another. Thus it is that in a thermo-couple the heat absorbed at the hot junction is greater than that evolved at the cold, the difference being the source of energy to which the thermo-E.M.F. is due.

The *Peltier effect* must not be confused with the *Joule effect* of a current in a circuit, for the former is *reversible*, the current heating or cooling the junction depending on its direction, while the amount of heat gained or lost respectively is proportional merely to the strength of current. In the Joule effect the junction is heated whichever way the current flows, and here the amount of heat is proportional to the square of the current (p. 54).

The total heat (H) developed in any circuit, which must always contain junctions, and hence be liable to Peltier effects, is at once obtained if the thermo-E.M.F. (E, in volts) produced at the heated junction be known, for the relation (p. 55) then becomes—

$$\begin{aligned} H &= 0{\cdot}239(C^2Rt \pm ECt) \\ &= 0{\cdot}239Ct(CR + E) \text{ calories.} \end{aligned}$$

The Thomson Effect is that discovered by Sir W. Thomson (Lord Kelvin), who found that a length of the same material, if hotter at one end than the other, is heated more by a current from an outside source flowing in one direction through it than if the same current flows in the opposite direction. Also that heat is absorbed or evolved from a conductor, according to the material it is made of, by the passage of a current through it when its ends are at different temperatures. For example, heat is absorbed by a copper conductor when a current flows from the cold to the hot end, and evolved when the current is reversed in direction. The opposite is the case with iron, while lead is the only metal not exhibiting the effect at all. For this reason, lead is taken as a standard of zero from which to measure the thermo-E.M.F. of other materials at all temperatures. A thermo-

electrical series of materials can thus be formed, showing the thermo-E.M.F. produced by heating the junction of a single couple, formed by such with lead, 1° C. higher than the rest of the circuit. When the thermo-E.M.F. acts from them to the lead, through the junction, they are called $+^{ve}$ elements; and when the E.M.F. acts from the lead to them, through the junction, they are called $-^{ve}$ elements. The following table gives the approximate values of the thermo-E.M.F.'s of different substances with lead for 1° C. difference in temperature between the hot and cold junctions:—

TABLE XVI

Substance.	Thermo-E.M.F. in Microvolts
[1] Bismuth, pressed wire	+ 89 to 97
Bismuth-antimony alloy (10 to 1)	+ 64·5
Bismuth, ordinary	+ 40
[1] Cobalt	+ 22
Nickel	+ 15·5
[1] German silver	+ 11·6
Palladium	+ 6·8
Mercury	+ 3·2
Lead	0
[1] Tin, pure wire pressed	− 0·1
[1] Copper, commercial	− 0·1
Tin, ordinary	− 0·4
[1] Platinum	− 0·9
[1] Gold	− 1·2
Cadmium	− 2·4
[1] Antimony, pure wire pressed	− 2·8
[1] Silver	− 3·0
[1] Zinc	− 3·7
[1] Copper, electrolytic pure	− 3·8
[1] Antimony, commercial wire pressed	− 6·0
[1] Arsenic	− 13·6
Antimony, ordinary	− 17·1
[1] Iron, pianoforte wire	− 17·5 to 22·6
[1] Red phosphorus	− 29·7
Antimony-zinc alloy (2 to 1)	− 99·0
Copper sulphide	− 196·7
Antimony-cadmium alloy (1 to 1)	− 231·9
[1] Tellurium	− 502
Selenium	− 807

The thermo-E.M.F. between 0° and 100° C. of couples formed of chemically pure lead and alloys of nickel-steel, platinum-iridium, aluminium-bronze, brass, German silver, and telegraph bronze has been determined by É. Steinmann (*Comptes rendus*, 130. pp. 1300-1303, May 14, 1900).

[1] Determined by Matthiessen. The remainder, together with cobalt, German silver, and platinum, determined by Becquerel.

Mr. G. Belloc (*Comptes rendus*, 134. pp. 105, 106, January 13, 1902) finds a 28 per cent nickel-steel to have a high thermo-E.M.F. amounting to 6300 microvolts at 196° to 400°, with an unusually high neutral point of 495°.

Mr. A. Heil (*Zeitschr. Elektrochem.* 9. pp. 91-97, January 29, 1903) gives a lengthy revised thermo-electric series in which the thermo-E.M.F.'s of a large number of elements and alloys with constantan (60 per cent copper, 40 per cent nickel) at various temperature differences are detailed. He has developed a new very efficient couple with constantan and the alloy antimony and zinc in the proportions 122 : 65. This gives + 0·045 microvolt for a temperature difference of 230° C., and + 0·130 microvolt for about 500° C.

For 1° C. difference in temperature between the hot and cold junctions of a single thermo-couple, made up of any two of the above substances, the E.M.F. in microvolts, or millionths of a volt, can at once be obtained by subtracting the lower one of the two in the table from the other. For example, the E.M.F. in microvolts of a

Nickel-lead couple = (15·5 − 0) = 15·5 from nickel to lead through junction ;
Lead-zinc couple = (0 − (− 3·7) = 3·7 from lead to zinc through junction ;
Cobalt-mercury couple = (22 − 3·2) = 18·8 from cobalt to mercury through junction ;
Cobalt-silver couple = (22 − 3) = 19 from cobalt to silver through junction ;
Gold-silver couple = − 1·2 − (− 3) = 1·8 from gold to silver through junction.

For 100° C. difference in temperature between the hot and cold junction, the E.M.F. would be 100 times that given above. With some couples, however, the E.M.F. varies with the temperature, but not directly proportional to it. For instance, the E.M.F. might be E at 100° C. and only 1½ E at 200° C., while the E.M.F. of another couple might fall with increase of temperature up to the *neutral point* at which there is no E.M.F., and then increase for further increments of temperature, as mentioned on page 386.

These effects may conveniently be studied by what is known as the *thermo-electric diagram* (Fig. 237), which shows the relation between the temperature and E.M.F. of the elements forming separate couples with lead. In this, the slope of the lines for the different metals shows the *Thomson effect* in each ; and it is seen that this is greatest in iron, very little in aluminium, and zero in lead. The E.M.F. in microvolts per degree of any pair of metals is given by the vertical intercept between them at the given temperature. For example, in an iron-zinc couple at 0° C. it = 15 ; at 100° C. = AB = 7 ; at the neutral point N, or point of intersection of the iron and zinc lines, it = 0, the temperature being almost 200° C. ; while at 300° C. it = CD = 7 microvolts, but acting in the opposite direction to that at AB. The arrow-heads show the direction through the hot junction.

Some couples have no practical neutral points, *e.g.* palladium-iron and copper-silver, these being reached either much below zero or at excessively high temperatures. The total or effective E.M.F. of a couple is obtained from Fig. 237 as follows. Let E be its total or effective E.M.F. when the temperature of the colder junction is T_1 and that of the hotter is T_2. Also let V be the E.M.F. of the more $+^{ve}$ metal of the couple with lead, and let v be the E.M.F. of the more $-^{ve}$ metal of the couple with lead, each at the mean temperature T° C. $= \left(\frac{T_1+T_2}{2}\right)^\circ$ C. Then $E=(V-v)(T_2-T_1)$ microvolts. For example, assuming an iron-zinc couple, let T_1 and T_2 be 50° C. and 150° C. Whence $T = 100°$ C., and at this temperature $V = -4$ and $v = -11$.

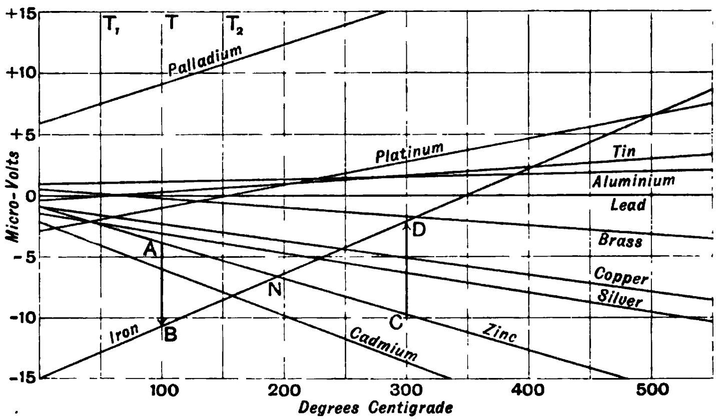


FIG. 237.—Thermo-electric Diagram showing Variation of E.M.F. with Temperature.

Therefore $E = \{-4-(-11)\}(150-50) = 7 \times 100 = 700$ microvolts. If AB be the *intercept* between the iron and zinc lines, *i.e.* the P.D. in microvolts between the metals (per degree C.) at the mean temperature (T), then $E = AB(T_2 - T_1)$ microvolts, where $AB = \{-4-(-11)\} = 7$.

We are now able to see the important bearing of a thermo-electric diagram on the design of thermo-couples, for it tells us that couples with a practical neutral point should either be avoided or that the range of temperature should be carefully chosen to obtain a good result. It will be seen that the actual E.M.F. of any of the couples is very small even when high differences of temperature are employed. To increase it, a number of similar couples can be connected together so that their individual E.M.F.'s are added together, the arrangement being then termed a *thermopile.* Fig. 238 indicates diagrammatically the principle, but not the exact form, of the usual method of constructing a thermo-pile. The two elements are connected end on to

each other in alternate order, and run nearly radially between a heating-chimney H and another cylinder C cooled by running cold water through it. One set of similar elements is shown by full lines, the other set by dotted lines. The heated junctions are therefore the even numbers 2 to 16, while the cold junctions are the odd numbers 1 to 17, the terminals of the pile being 1 and 17. The individual E.M.F.'s all act in the same direction, so that the total E.M.F. = the E.M.F. of one couple multiplied by the number of couples. Fig. 238 shows eight couples in series.

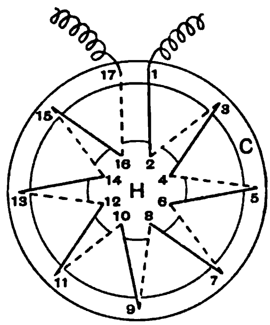


FIG. 238.—Principle of a Thermo-pile.

A thermo-pile commonly met with is that of Clamond, using iron with an alloy of antimony and zinc for each couple. 6000 of these, heated by coke, gave 109 volts, with a terminal resistance of 15·5 ohms. The choice of substances should rest with two as far apart in the table, page 388, as possible, providing neither is too easily fused or oxidised.

The author has for some years been using a thermo-electric generator, made by Mr. H. Barrington Cox, which is capable of giving a current of 3·5 amperes on short circuit and an E.M.F. of 5·0 volts on open circuit, the internal resistance increasing with the current from 1·05 to 1·45 ohm. The generator is about 6 in. long by about 6 in. in diameter, and has a water-jacket on the outer periphery. A central bunsen flame is spread out over, but does not actually touch, the walls of the central cylindrical hole.

Efficiency of Thermo-Electric Generators.—This is very low at present, but it is quite possible that means may be found to increase it. According to Fischer, some years ago, only from 0·3 to 0·5 per cent of the heat energy is converted into electrical energy, and it is doubtful whether this figure reaches 1 per cent in present-day thermo-piles.

As is the case with many other phenomena, *e.g.* self-induction (p. 194), thermo-E.M.F.'s may be either very usefully employed or their presence may be most undesirable. An instance of their use is in electro-metallurgical work, especially abroad; also in the measurement of temperature (p. 273): while, on the other hand, their presence is most undesirable and a source of inconvenience in some kinds of electrical testing.

The Production of E.M.F. Chemically: Primary Cells.—Of the various ways and means for obtaining an electro-motive force, some

of which have already been considered, that resulting from the transformation of chemical energy into electrical energy is one of the most important. The chemical action which causes the transformation and produces E.M.F. may be of two kinds, namely :—

1. A decomposition and reduction of one or more substances from one form to quite a different form, the original state not being obtainable again by a reversal of the primary action.

2. A decomposition and formation of one or more substances without change of form, and their subsequent re-formation by secondary or reversed action.

We will now consider the various electro-chemical appliances which answer to the first-named principle, and which are called voltaic, galvanic, or primary cells.

When any two metallic substances are placed in a solution which is able to attack one of them more than the other, an E.M.F. is set up between them, and the arrangement constitutes a primary cell. If the metals are connected through a conductor outside the cell, this E.M.F. will cause a current to flow, its *direction inside the cell being from the more +^{ve} metal to the other*, and therefore in the opposite direction in the conductor. The more +^{ve} metal is the one which attracts oxygen, *i.e.* oxidises, the most readily of the two used. It is therefore possible to arrange the various elements in order, according to their chemical affinity for oxygen, which is identical with the contact series of the elements *in air.* The order indicates *decreasing affinity for oxygen*, or, in other words, is such that each element becomes positively electrified when in contact (*in air or liquid*) with any other below it in the series. The following elements are thus arranged in order :—

+ Magnesium
Zinc
Iron
Cobalt
Nickel
Lead
Tin
Bismuth
Copper
Mercury
Silver
Platinum
Gold
Hydrogen
Antimony
− Carbon

It will now be convenient to consider one of the simplest forms of primary cell, which, although not used in practical everyday work,

will serve to illustrate fundamental principles and to show how undesirable attributes have been improved or eliminated. The construction is shown in Fig. 239, and consists of two plates, one of copper (C), the other of zinc (Z), dipping into an oxidising solution such as a dilute solution of sulphuric acid and water, which is contained in a glass or glazed earthenware vessel V. The plates Z and C are connected to the terminals B and A of the cell by stout wires. If the plates Z and C are practically pure, then no action of any description takes place by reason simply of their immersion in the solution; but if an external circuit R is connected to A and B, a current at once flows in the direction of the arrows.

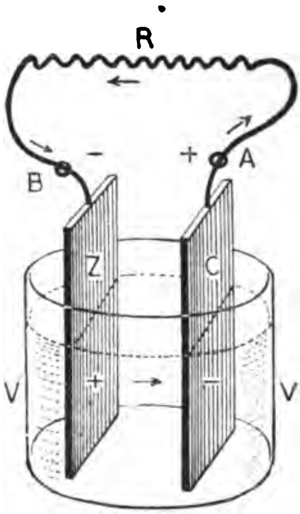


FIG. 239.—Simple Voltaic Cell.

The flow of current, as long as it lasts, is accompanied by a gradual consumption of the zinc plate Z, but this ceases when the circuit through R is opened and the current in consequence stopped. Whether the cell is on open circuit or giving current, the copper plate C is not acted on chemically at all, so that what really happens when a current flows is this: The zinc and oxygen liberated combine to form zinc oxide, which is at once attacked by the sulphuric acid, and zinc sulphate formed. The hydrogen gas produced in the decomposition, although evolved at the surface of the zinc plate, is liberated from the copper plate (*vide* p. 37). Now the chemical symbol of zinc is Zn, of copper Cu, of hydrogen H, of oxygen O, and of sulphur S, so that the composition of a compound composed of two or more of these elements is at once known by its chemical symbol. For example, sulphuric acid is represented by the symbol H_2SO_4, meaning that each molecule, or smallest particle which can exist in a free state, consists of two atoms of hydrogen (H_2), one of sulphur (S_1, or simply S), and four of oxygen (O_4). The chemical action inside the above cell can therefore be stated as follows:—

Zinc and sulphuric acid produce zinc sulphate and hydrogen, or

$$Zn + H_2SO_4 = ZnSO_4 + H_2.$$

Thus the zinc and acid are used up, while zinc sulphate and hydrogen are formed, the electrical energy resulting being the equivalent of the

chemical work done in the cell, which is therefore an electro-chemical transformer of energy.

As the current flows from A to B through R (Fig. 239), the terminal A is called the $+^{ve}$ pole, and B the $-^{ve}$ pole; while the plate C is the $-^{ve}$ element, and Z the $+^{ve}$ element. Zinc being a readily oxidisable metal, and standing high in the list (p. 392) as an electro-positive element, it forms the $-^{ve}$ pole or $+^{ve}$ element in nearly every primary cell. Carbon, platinum, silver, and copper, on the other hand, being much less oxidisable than zinc, and standing high as electro-negative elements, are used as the $+^{ve}$ poles or $-^{ve}$ elements in various types of primary cells. From what has now been said, it follows that a cell will be most efficient, and have the highest E.M.F., when it employs elements which are farthest apart from one another in the series (p. 392).

Polarisation.—The hydrogen gas liberated from the copper plate (Fig. 239) sticks to it in considerable quantity, and covers much of its surface after the cell has been sending a current for some time. This is very objectionable for two reasons, namely: (1) it increases the internal resistance (that from plate to plate) of the cell by diminishing the effective surface of the plate, all gases being bad electrical conductors; (2) it creates a counter, or back, E.M.F. in the cell, for hydrogen, being electro-positive to zinc and as oxidisable, forms temporarily an electro-chemical couple with the zinc plate Z, and sets up a back E.M.F. from the more $+^{ve}$ element, the hydrogen film, to the more negative element, zinc. The effective terminal E.M.F. of the cell is therefore the difference between the proper Zn to Cu E.M.F. and the temporary H to Zn E.M.F., so that both the E.M.F. and current fall off, and the cell is said to be *polarised.*

The most successful remedies against internal polarisation are of a chemical and electro-chemical nature. For instance, if a highly oxidising substance, such as manganese peroxide, peroxide of lead, oxide of copper, potassium bichromate, or chloride of lime (bleaching powder), is added to the acid, the hydrogen gas produced is destroyed while in the nascent state, usually with the formation of water. Such depolarising agents attack certain of the elements, *e.g.* copper, and hence can only be used in carbon-zinc or platinum-zinc cells. An electro-chemical remedy is to arrange matters so that a metal, instead of hydrogen, is liberated at the $-^{ve}$ *element.*

Local Action.—This results from using commercial instead of pure elements, and is confined mostly to the zinc. To understand what goes on, imagine one of a large number of particles of impurities, such as iron, to be in contact with the solution, and making a much poorer

contact with the surrounding zinc. Then the preceding principles tell us that a local internal current will be set up from all the zinc particles in the neighbourhood to this one of iron, no matter whether the cell is on open or closed external circuit. The zinc will therefore gradually consume away, giving rise to what is known as *local action*, *i.e.* the production of useless internal currents. This can be eliminated by using pure zinc; but as this is very much more expensive than commercial zinc, the latter is always used, in which case local action is minimised by amalgamating the zinc, *i.e.* covering up the impurities, from contact with the solution, by means of mercury. This is done by first *cleaning* the zinc with dilute sulphuric acid, and then, while it is wet, rubbing over it, with a rag, two or three drops of mercury. The plate attains a bright silvery lustre, and is coated with an amalgam of mercury with the particles forming the surface of the plate. Excess of mercury must be avoided, as it only makes the zinc plate brittle; and, further, this latter must be quite clean, or the mercury will not amalgamate with it. A better way is to add about 4 per cent of mercury to the molten zinc before casting it into plates or rods. It prevents the wasting away of the zinc when the cell is sending no external current by covering up the impurities in the zinc, while in no way affecting its action when sending current. The E.M.F. of a cell with its zinc plate amalgamated is not, however, as constant as it would be with a plate of pure zinc.

Desiderata in a Good Cell.—1. Its E.M.F., which in a cell of given materials is entirely independent of the shape and size of the parts, should be constant, and as high as possible.

2. Its internal resistance should be small, which is obtained by having the plates large and close together, and the intervening substance of good conductivity.

3. It should be free from polarisation and local action.

4. It should have plenty of working material, which should not be of an expensive nature.

Although many good primary cells exist, none fulfils every one of the above requirements simultaneously. Primary cells may be classified into (1) single-fluid cells, (2) two-fluid cells, (3) dry cells; but space will not permit of description of more than one or two of the most prominent examples of each class in everyday use.

The Bichromate Cell.—This is of the single-fluid type, containing the depolariser bichromate of potash or of soda, and was devised by Poggendorff. It consists (Fig. 240), in the bottle form, of two fixed carbon plates connected electrically to the left-hand terminal. Between these carbon plates, and carried by a metal rod which can slide up

and down and be clamped in a central guide, is a zinc plate electrically connected to the right-hand terminal. This arrangement enables the zinc plate to be raised out of the solution when the cell is not in use, thus preventing it from wasting away through local action. The solution consists of sulphuric acid, water, and potassium bichromate, and the best results will be obtained with the following proportions: 1 pint of concentrated sulphuric acid (sp. gr. 1·845), 11 pints of cold water (H_2O), and 1 lb. of powdered potassium bichromate ($K_2Cr_2O_7$). When a current is given by the cell, the chemical changes may be represented by the relation—

FIG. 240.—Bichromate Cell (bottle form).

$$K_2Cr_2O_7 + 7H_2SO_4 + 3Zn = 3ZnSO_4 + K_2SO_4 + Cr_2(SO_4)_3 + 7H_2O,$$

from which we see that zinc sulphate ($ZnSO_4$), potassium sulphate (K_2SO_4), and chromium sulphate ($Cr_2(SO_4)_3$) are formed besides water.

The bichromate cell is also made up in a slightly different form, shown in Fig. 241, in which the carbon plate or rod is contained in a porous pot of unglazed earthenware. Surrounding this is a cylindrical zinc plate provided with a connecting lug or strip, and containing all, is an outer glazed earthenware jar. The porous pot contains a solution of potassium bichromate and sulphuric acid, while the zinc plate is immersed in ether dilute sulphuric acid or a solution of common salt (NaCl) and water. In the first case the chemical action is that given above; in the latter case, with the salt solution, zinc chloride ($ZnCl_2$) is formed instead of zinc sulphate, and sodium sulphate (Na_2SO_4), in addition to chromium sulphate.

FIG. 241.—Bichromate Cell with Porous Pot.

The bichromate cell gives an E.M.F. of about 2 volts, and has an internal resistance of from 0·5 to 2 ohms, according to the type of cell and its condition, whether newly made up or requiring a recharge with solutions, etc. An excess of the bichromate should always be present, for the cell begins to fail when this is exhausted, the

orange colour of the solution turning blue. When this is observed, more bichromate should be added; but if the cell fails without the solution changing colour, then more acid or salt, as the case may be, is required. No fumes are given off from the cell, but the E.M.F. falls after it has been sending a current for a little time, recovering, however, when the cell is allowed to rest. The E.M.F. falls very slightly for large increases of temperature.

The Léclanché Cell.—This is a *one-fluid* cell having a solid oxidising or depolarising agent, and is used very extensively in practice for giving intermittent currents. It consists (Fig. 242) of an outer glass jar containing a solution of sal-ammoniac (ammonium chloride) with water, and some surplus crystals of this substance undissolved at the bottom. A cylindrical zinc rod, to the upper end of which a copper connecting-wire is attached, dips into the solution. Immersed also in this is a porous pot of unglazed earthenware containing a carbon plate packed in tightly with granules of broken gas carbon mixed with the depolarising agent, manganese peroxide (MnO_2). The mouth of the porous pot is sealed with a layer of pitch, in which two small tubular vent-holes are left for enabling solution to be poured in through one of them and gas or air to escape through the other. The terminal screw is fixed either to the carbon cap which forms the end of the carbon plate, or to a lead cap cast on to the end of the plate. In this latter case the lead cap is practically riveted on to the plate by the lead running into two or three small holes drilled sideways through the end of the carbon plate. The contents of the porous pot should be free from dust, so that as much of the surface of the carbon plate and packing as possible is presented to the solution. The function of the porous pot is merely to keep the contents together, and not to keep the solution out. In fact, to enable a new cell to be used at once, solution must be poured into the pot as well as into the outer jar, otherwise time must be allowed for the solution in the outer jar to diffuse through the porous pot and fill the spare spaces in it before the cell will work. The rim of the outer jar should

FIG. 242.—Léclanché Cell (bell form).

be dipped into some enamel compound so as to prevent the solution *creeping* over the rim of the jar to the outside.

The chemical action taking place when the cell sends a current may be represented by the following equation :—

$$Zn + 2NH_4Cl + 2MnO_2 + C = C + ZnCl_2 + Mn_2O_3 + 2NH_3 + H_2O.$$

The white salt zinc chloride ($ZnCl_2$), manganese sesquioxide (Mn_2O_3), and water (H_2O) are formed, while ammonia gas (NH_3) is given off. The hydrogen gas, which tries to get to the carbon plate, is oxidised slowly by the MnO_2, so that if the cell is made to give current for some time, the hydrogen is not oxidised quickly enough, and polarisation sets in. The E.M.F. consequently falls, but recovers its original value when the cell is allowed to rest, and when the MnO_2 therefore has time to reduce the hydrogen to water. The cell begins to fail when the solution turns milky, for this means that the sal-ammoniac is exhausted, while zinc oxide is being formed instead of zinc chloride. More sal-ammoniac should be added when this is observed. If, however, the cell fails without the solution turning milky, more MnO_2 is required for oxidising the hydrogen. The carbon undergoes no chemical change at all, and will last for any length of time, but the zinc gradually wastes away, furnishing with the sal-ammoniac the electrical energy developed.

The particular form shown in Fig. 242 is known as the 'bell' form, from it being so generally employed for ringing electric bells. The Léclanché cell stands pre-eminently suitable for such intermittent-current work, and will run for many months without any attention other than adding a little water occasionally to supply the place of what has evaporated. The E.M.F. is about 1·47 volt, and the internal resistance may be anything from $\frac{3}{4}$ to 2 or 3 ohms, according to the size of the plates, their distance apart, the density of the solution, and thickness of the porous pot.

When a cell with a smaller internal resistance is required, the so-called agglomerate form of Léclanché (Fig. 243) is employed. It consists of a central fluted carbon rod carrying the terminal block. Each of the fluted grooves in this rod contains a cylindrical rod composed of a mixture of powdered carbon and manganese peroxide with some binding material to cement the mixture together when formed under pressure into rods. These rods are held up against the fluted carbon rod by a tight wrapping of coarse canvas with two india-rubber bands outside. No porous pot is necessary, and the cylindrical zinc plate surrounds the canvas, the whole being contained in an outer glazed earthenware jar, as shown in Fig. 243, which contains the

usual solution of sal-ammoniac. The internal resistance of this agglomerate form may be as low as 0·3 ohm when the cell is in good condition.

Other modifications of the Léclanché cell are in use. One of these employs a sack of coarse canvas instead of the porous pot; otherwise, the construction is precisely that of the 'bell' form. In another type, the zinc rod is contained in a central porous tube which is fixed to an outer carbon cylinder, the space between being filled with pellets of gas carbon and manganese peroxide. The internal resistance is somewhat less than that of the 'bell' form owing to the absence of the porous pot.

FIG. 243.—Agglomerate Léclanché Cell.

Dry Cells.—These are, one and all, modifications of the Léclanché cell, and contain no liquid that can spill. The name is a misnomer in the sense that the contents are not perfectly dry, but comprise a wet jelly-like mass or paste instead of liquid. Well-known types commonly met with are the *Obach*, the *Century*, the *E.C.C.*, the *V.*, the *E.S.*, and the *Dania*. As the construction is much the same in all of them, we may merely indicate the general principles involved.

The elements employed are carbon and zinc, the latter being in the form of a rectangular or cylindrical pot which is covered on the outside with cardboard or paper. This zinc pot is the +^{ve} element or −^{ve} pole of the cell, and contains the carbon plate in the centre, but without touching it. The intervening space is filled with a mixture of coarsely powdered carbon, manganese peroxide, sal-ammoniac, and often a small percentage of zinc sulphate, the whole being made into a stiff paste by the addition of water and glycerine. These last-named only serve to bind the other ingredients together, and take no part in the chemical action in the cell. The contents are sealed in by a layer of pitch at the top, through which two tubular vent-holes are inserted for the escape of gas, etc.

Fig. 244 shows three V dry cells connected in series in a box with terminal screws at the ends. The E.M.F. of all types of dry cell is about 1·55 volt, while the internal resistance of new cells may be from 0·015 to 0·5 ohm. A V dry cell 3 ins. diameter by

7 ins. high and weighing 3·06 lbs. is rated to give a current of $7\frac{1}{2}$ to 10 amperes at 1·55 volt, or about 40·35 watt-hours, when discharging through an external circuit of 6 ohms, the internal resistance being 0·015 ohm. Also, a V dry cell $1\frac{1}{2}$ in. by 4 ins., weighing 0·53 lb., gives $2\frac{1}{2}$ to 4 amperes at 1·5 volt, or about 5·93 watt-hours, through 12 ohms, with an internal resistance of 0·3 ohm. Dry cells gradually polarise, and their E.M.F. slowly diminishes on discharge, but recuperates somewhat during rest. The internal resistance slowly increases with discharge, and the current given is much greater than that obtainable from ordinary primary cells on account of the smaller internal resistance.

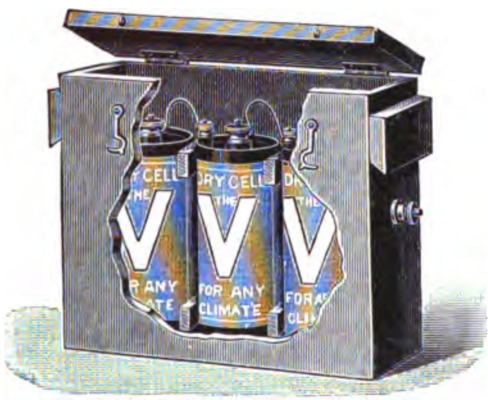


Fig. 244.—Battery of Three V Dry Cells.

The Dania dry cell made by the Atlas Carbon and Battery Company, of London, differs from all other dry cells in that the agglomerate mixture is contained in a linen sack, which is very carefully tied in all directions by hand, and the electrolyte is in the form of a jelly. The advantages claimed by this mode of construction are low internal

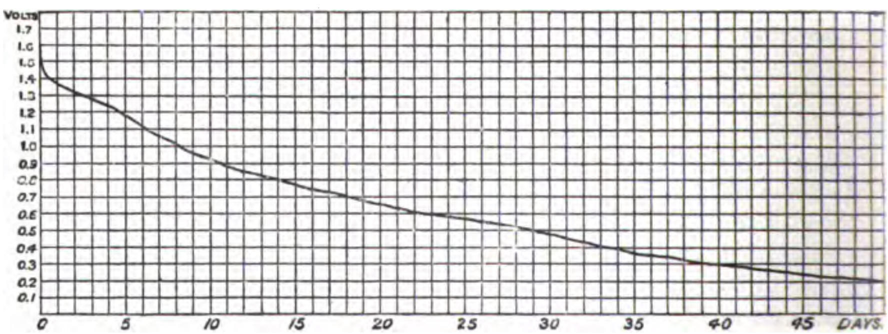


Fig. 245.—Curve of Discharge of a 'Dania' Dry Cell through a Constant External Resistance.

resistance and absence of local action while the cell stands idle. These claims are well substantiated by the fact that the Dania cell is practically the only cell which can be stocked for long periods without serious

drop in E.M.F. Fig. 245 shows the fall of terminal E.M.F. of a 'C' size (7-in. × 2¾-in. diameter) Dania dry cell when discharged continuously through a constant external resistance of 15 ohms for 50 days. The internal resistance was 0·13 ohm at the start, 0·47 on the seventh, and 1·71 ohm on the fiftieth day. Total output = 30·9 watt-hours.

FIG. 246.—Daniell Cell.

The Daniell Cell.—This is an example of a *two-fluid* cell having a remarkably constant E.M.F. and showing very little polarisation. One form of it consists (Fig. 246) of a small copper cylinder inside a porous pot containing a solution of copper sulphate and water. This is again immersed in an outer glass or glazed earthenware jar containing either dilute sulphuric acid or zinc sulphate in which dips a cylindrical zinc plate as shown.

The chemical action taking place on the cell sending a current is as follows: In the outer jar

$$Zn + H_2SO_4 = ZnSO_4 + H_2.$$

The hydrogen gas thus produced travels through the acid solution and porous pot, and, coming in contact with the copper solution in the latter, at once displaces an electro-chemically equivalent quantity of copper. Thus, in the inner jar,

$$H_2 + CuSO_4 = H_2SO_4 + Cu,$$

the copper being deposited on the copper plate instead of hydrogen, as was the case in the cell (p. 393).

In this way polarisation is entirely prevented by *electro-chemical* action (*vide* p. 394) so long as the copper sulphate solution remains saturated. This is ensured by always having a supply of the crystals of $CuSO_4$ at the bottom, which are therefore gradually used up. The copper plate gradually grows by the deposition of copper on it, while the zinc plate wastes away to form zinc sulphate; thus sulphuric acid is gradually neutralised in the outer jar and formed in the copper sulphate solution. If a semi-saturated solution of zinc sulphate be used instead of the dilute sulphuric acid, the zinc still wastes away, and thereby increases the density of the $ZnSO_4$ solution. With sulphuric acid, the E.M.F. is higher, but not so constant, and the internal resistance lower, than when $ZnSO_4$ is used; for the E.M.F.

is increased by increasing the density of the $CuSO_4$ solution, and diminished by increase in density of the $ZnSO_4$ solution. The E.M.F. of a Daniell cell ranges from 1·07 to 1·14 volt, depending on the densities of the solutions and purity of the plates. The internal resistance ranges from ½ to 3 ohms, according to the construction and the state in which the cell is in. The cell begins to fail when all the acid and copper sulphate solutions are reduced, the former having the composition of 1 of acid to 12 of water to commence with. The E.M.F. very slightly increases for a large increase of temperature.

The Clark Standard Cell.—Invented by the late Mr. Latimer Clark, this cell is a very important one, and is designed solely as a standard of E.M.F. for electrical measurement. Precise instructions have been issued by the Board of Trade for the construction of this cell, and these are detailed in *Practical Electrical Testing* by the author.

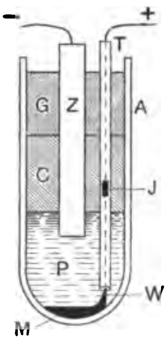


FIG. 247.—Clark Standard Cell.

One method of setting up the cell is shown in sectional elevation (Fig. 247), and consists of an outer containing glass vessel or test-tube A. In the bottom of this rests a closely wound flat spiral (like the hair-spring of a watch) of thin platinum wire, terminating in the straight portion WJ. This spiral is coated with mercury by dipping it while red-hot into a little pure redistilled mercury, or preferably by dipping it cold into boiling mercury. The mercury then adhering, constitutes the $-^{ve}$ element, and the wire making contact with it, the $+^{ve}$ pole of the cell. A globule of mercury M is often placed at the bottom of A, in contact with the spiral. A paste P, composed of pure mercurous sulphate and a saturated solution of pure zinc sulphate, is inserted on the top of M. A pure redistilled zinc rod Z is inserted through a cork C and dips into P, the upper end being soldered to a copper wire, by means of which connection is made to the $-^{ve}$ terminal of the cell. Another copper wire is soldered to the platinum wire at J, and this, together with WJ, is enclosed in a thin glass tube T, which passes through C and insulates this 'leading-in' wire from the contents of the cell. This wire is connected to the other or $+^{ve}$ terminal of the cell. A layer of marine glue G is poured while hot over C, and when cold securely fixes Z and T in position and seals the cell. Owing to the small quantity of mercury used, this form of the cell, suggested by Dr. Muirhead, is portable, and can be inverted without fear of the mercury being displaced. The cell being a standard of E.M.F., it must not be allowed to send any but an infinitesimally small current,

and for this reason should be used with at least 5000 ohms in series.

Mr. W. R. Cooper (*Electrician*, 40. p. 748, 1898) has given some figures showing the constancy or permanency of the E.M.F. of Clark's cells, set up according to Board of Trade specification, with time. Cells initially accurate to 1 part in 7000, at the end of 3½ years showed a mean error of 1 in 700 too low, others of 1 in 500 after 2¾ years.

Mr. A. Campbell (*Phil. Mag.* 45. pp. 274-276, 1898, and *Electrician*, pp. 601-603, September 1895) has devised some ingenious temperature compensators for use with standard cells, the object being to always have the same P.D. between two points of the arrangement at any temperature ordinarily met with in practice.

The chemical action occurring during the passage of a current from the cell is a decomposition of the mercurous sulphate, the mercury of which is added to M, an equivalent quantity of the zinc Z being dissolved. The contents of the cell must be quite pure, the zinc rod Z and mercury M being redistilled, while the mercurous and zinc sulphates must also be pure.

The E.M.F. of the cell is 1·4340 legal volt at 15° C., and this value is not only constant when the cell is only allowed to send extremely small currents, but it is reproducible in all cells made with the same precautions. The E.M.F. decreases with increase of temperature, its temperature coefficient being 0·07 per cent per 1° C. Hence the E.M.F. at any temperature t° C. can be found from the relation

$$\text{E.M.F.} = 1{\cdot}4340\{1 - 0{\cdot}0007(t - 15^\circ)\} \text{ volts.}$$

The internal resistance is high, and for cells 2 cms. diameter with electrodes 3 to 4 cms. apart, at ordinary temperatures, is usually from 40 to 80 ohms. A change of temperature from 30° to 5° C. trebles this resistance. The resistance of Clark cells diminishes with increase of temperature, with the time during which they give current, and with the magnitude of this current. In a certain Clark cell, at a temperature of 13·1° C., an increase of current from 2·43 to 141 microamperes produced a diminution of internal resistance from 234·7 to 177·8 ohms. At 29·21° C. the same variation of current reduced the resistance from 125·3 to 80·4 ohms, the duration of current being four minutes. An increase in the duration of this diminished the resistance still further. For a constant current of about fourteen microamperes, temperatures of 13·1° C., 17·5° C., 21° C., and 29·2° C. gave internal resistances of 217·5, 195·7, 126·1, and 95·2 ohms respectively.

Weston Standard Cadmium Cell.—This cell, originally suggested by Mr. Weston, is taking so prominent a position as a standard of E.M.F. that a brief description will not be out of place here. It has the great advantage over the Clark cell that its temperature coefficient of variation of E.M.F. over the ranges of temperature met with in testing practice is practically negligible. Thus its mean temperature coefficient for a range of 18° C. to 32° C. = $-0{\cdot}00002_5$ volt per rise of 1° C., its E.M.F. at 18° C. being 1·0195 volt. The close agreement between cells of different makes, which is of such importance, is seen by the fact that the E.M.F.'s, at 10° C., of a Reichsanstalt and Weston Company's cell were 1·01925 and 1·01905 volt, and at 30° C. they were 1·01855 and 1·01915 volt respectively. The internal resistances were 2000 and 150 ohms respectively, the former diminishing greatly, the latter slightly, with increase of temperature.

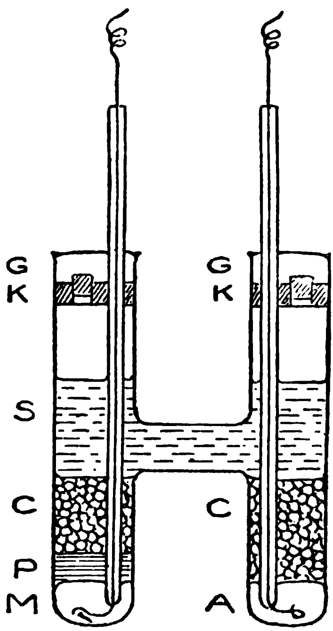


FIG. 248.—Section of Cadmium Standard Cell.

A section showing the construction (Fig. 248) of the H form, originally suggested by Lord Rayleigh, and recommended by the 1905 Report of the Standards Committee of the British Association, is now made in this country by the Cambridge Scientific Instrument Company. Two short glass tubes, connected by a cross tube, contain mercury M at the bottom, into which dip platinum wires enclosed in small glass tubes which lead the wires from the bottom to the top of the cell. P is a paste, and C cadmium sulphate crystals. S is a saturated solution of cadmium sulphate. The vertical limbs are closed by corks K, which are sealed by marine glue G. The cells can otherwise be hermetically sealed, and the platinum wires fused through the bottom of the limbs. Fig. 249 shows a general view of two cells mounted.

Other forms of standard E.M.F. cells exist, but none are so universally used as the Clark cell. A large number of primary cells, other than those already described, have been devised from time to time, but, as comparatively few of them are used in practical work, the description of them will be deferred.

Design and Maintenance of Primary Cells.—It is important to

remember that *the E.M.F. of any cell is entirely independent of its size, shape, and relative disposition of the parts.* A cell with a greater E.M.F. can be made by choosing elements farther apart on the contact potential series (*vide* p. 392), and by a choice of electrolyte such that one element is unaffected, the other being actively acted on by the electrolyte. The purer the materials used, the smaller the consumption of such for any given output of electrical energy; the less the waste in the cell, while at rest, due to local action; and the greater the E.M.F. Constancy of E.M.F. on discharge will depend on the elimination of polarisation and local action, and on the cleanliness of the cell. The most effective means of eliminating polarisation is by immersing the $-^{re}$ element in such a solution as will most readily exchange its metallic constituent (which is deposited on the $-^{re}$ element) for the gas which is produced at the $+^{re}$ element and tries to reach the $-^{re}$ element (*vide* pp. 394 and 401).

FIG. 249.—Standard Cadmium Cell.

Local action is avoided by the use of pure materials. Cleanliness and good condition entail the renewal of ingredients when reduced or exhausted, the prevention of the formation of crystals of salts and dirt on the different parts of the cell. The stronger the current desired, the lower must be the internal resistance, which is effected by having the plates larger and closer together, the intervening space offering a low resistance.

Pre-determination of the E.M.F. of Primary Cells.—Comparing what was said about electrolysis (p. 37 *et seq.*) with the foregoing pages on primary cells, the close connection between electricity and chemical affinity will at once be seen. Thus electricity can be obtained by *chemical combination* in a voltaic cell, due to the reducing down of potential energy of chemical affinity; and, conversely, *chemical separation* is produced by electricity in a voltameter. Now energy in the form of heat is either absorbed or developed whenever a chemical

change takes place in one or more substances; and, as we have just remarked, this heat energy is *transformed*, and *not evolved*, in a voltaic cell, into electrical energy. Moreover, the formation of chemical compounds liberates heat, while their separation is accompanied by an absorption of heat.

Hence, let a cell having an E.M.F. of E volts send a current of A amperes through an external circuit in which all the electrical energy is transformed into heat.

Then, if J stands for Joule's mechanical equivalent of heat, the quantity of heat absorbed per second in the external circuit equals $\frac{EA}{J}$.

Further, let H_1 units of heat be absorbed per gramme of the substance separated chemically in the cell, and Z_1 be the electro-chemical equivalent of this substance (p. 40).

Then AH_1Z_1 is the total amount of heat absorbed chemically per second in the separation.

Likewise, if H_2 units of heat be evolved per gramme of some other substance formed chemically in the cell, and Z_2 be its electro-chemical equivalent, then AH_2Z_2 is the total amount of heat evolved chemically per second in the formation, and we must therefore have

$$AH_2Z_2 = \frac{EA}{J} + AH_1Z_1,$$

or

$$E = J(H_2Z_2 - H_1Z_1),$$

$$= JZ_H\left(H_2\frac{w_2}{v_2} - H_1\frac{w_1}{v_1}\right) \text{ volts},$$

where w_1 and w_2 are the atomic weights, $v_1\,v_2$ the valencies of the substances (*vide* p. 41), Z_H the electro-chemical equivalent of hydrogen $= 0{\cdot}00001038$ gramme per coulomb, and $J = 4{\cdot}184$ joules.

The terms inside the brackets of the last relation, each of the general form $H\frac{w}{v}$, are the heats of formation and separation of the substances, *i.e.* the energy evolved or absorbed in the electro-chemical reaction consequent on the production of current sufficient to liberate 1 gramme of hydrogen in a voltameter. The expression in brackets, therefore, is the total amount of heat in calories usefully employed in producing electrical energy.

In the case of a Daniell cell (p. 401), zinc sulphate ($ZnSO_4$), having a heat per gramme equivalent equal to 53,450 calories, is formed, and copper sulphate ($CuSO_4$, 28,200 calories) decomposed in the working of the cell. Hence its E.M.F. is

$$
\begin{aligned}
E &= JZ_H\left(H_2\frac{w_2}{v_2} - H_1\frac{w_1}{v_1}\right) \\
&= 4{\cdot}184 \times 0{\cdot}00001038(53450 - 28200) \\
&= 0{\cdot}00004343 \times 25250 \\
&= 1{\cdot}096 \text{ volt approximately.}
\end{aligned}
$$

A small correction for temperature (about 0·00003 volt per 1° C.) should be applied to this figure, as the Daniell cell has a $+^{ve}$ temperature coefficient, *i.e.* its E.M.F. rises on heating. But, even after inserting this, the value above must only be regarded as roughly approximate, for the thermo-chemical data available are not susceptible of a high degree of accuracy. This is realised by comparing the heats of formation and separation of the same substance as determined by three different authorities, and which in some cases differ by as much as 12 per cent. A large collection of heat determinations, as made by Thomson, Berthelot, and others, will be found in *Thermochemie*, vol. ii., by M. Berthelot.

There are two or three ways of giving heats of formation, namely, in calories liberated by one formula weight (in grammes) of the compounds. For example, 68,360 calories are produced when 2 grammes of H unite with 16 of O to form 18 of water, or $H_2 + O = H_2O$. Since, however, calories of grammes equivalent equal

$$\frac{\text{calories of formula weight}}{\text{valency}},$$

34,180 calories will be produced by 1 gramme of H uniting with 8 of O to form 9 of water.

The figures given for the Daniell cell are in gramme equivalents. If, however, they were in terms of a formula weight, then

$$E = \frac{0{\cdot}00004343 \times \text{heat of formation in calories}}{\text{valency}},$$

As, however, in most primary cells, and in all lead cells, we have to deal with divalent elements in which the equivalents are only half the atomic weights,

$$E = \frac{0{\cdot}00004343 \times \text{heat}}{2} = \frac{\text{heat}}{46040}.$$

Hence, for 1 volt to be set up in any electro-chemical action it is necessary for a net heat of formation of 46,040 calories to be evolved by 1 gramme equivalent of the compound formed.

If H be the actual heat in any case, and τ° C. the room temperature,

$$E = \frac{H}{46040} + \tau\frac{dE}{dt},$$

where $\frac{dE}{dt}$ equals the rate of change of E.M.F. with τ, *i.e.* the temperature coefficient of the cell, which is often negligibly small.

Thus in a Daniell cell $E = \frac{106900 - 56400}{46040} + 0{\cdot}00003 = \frac{50500}{46040} = 1{\cdot}096$ volt.

Again, the heat of formation of water per gramme molecule equals 68,360 calories.

$\therefore$ E.M.F. necessary to just produce decomposition equals $\frac{68360}{46040} =$ 1·48 volt.

Methods of Grouping Cells, and the Effect.—When two or more cells are electrically connected, so as to help one another in sending current through an external circuit, the combination is termed a *battery*. The cells of a battery may be connected up in one of the three following ways, each of which has advantages in a particular case: (A) all in series; (B) all in parallel; (C) partly in series and partly in parallel, when the number of cells is *even*. In order to compare these methods of grouping, let us, for the sake of definiteness, consider a battery of four cells in each case successively.

Cells all in Series.—This is represented symbolically in Fig. 250, where the long thin line represents the $+^{ve}$ pole and the short thick line the $-^{ve}$ pole. The current flows from the thin to the thick extreme lines of the series, through the external circuit; and the connections from cell to cell are not shown but are understood. Now with all the cells in series, the same current flows through each, and hence the *same* amount of chemical decomposition takes place in each cell. Hence the total E.M.F. (E) of the battery will be the sum of the E.M.F.'s (e) of the several cells; or, if they are all of the same type, but not necessarily of the same size, and there are S cells in series, we have

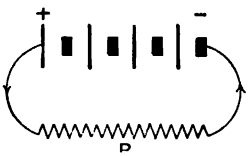


FIG. 250.—Battery of Cells all in Series.

$$E = Se.$$

The total internal resistance (B) of the battery will vary directly with the number of cells in series, so that if b is the resistance of each cell, we have

$$B = Sb.$$

Hence, by Ohm's Law, the current (A) which this battery would send through an external resistance (R) is

$$A = \frac{Se}{Sb + R}.$$

Cells all in Parallel.—This is depicted in Fig. 251, and here each cell supplies only a fraction of the total current. Therefore, since *the amount of chemical action in a cell is proportional to the quantity of electricity*

which passes through it, i.e. *to the current*, the total amount of chemical action is the same as if the whole current from the battery passed through one cell. Hence

$$E = e.$$

The internal resistance, however, is reduced in proportion to the number of cells in parallel, for connecting them in parallel has the same effect as increasing the size of plates and area of solution through which the current has to pass. Therefore

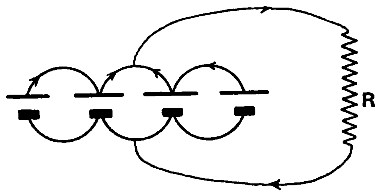


FIG. 251.—Battery of Cells all in Parallel.

$$B = \frac{b}{P},$$

where P is the number of cells in parallel, and hence

$$A = \frac{e}{\frac{b}{P} + R}.$$

Cells in Series-Parallel Combination.—This is shown in Fig. 252, and is a combination of the above two arrangements, so that we now have

$$E = Se,$$

and

$$B = \frac{Sb}{P}.$$

Therefore

$$A = \frac{Se}{\frac{Sb}{P} + R}.$$

Now if N equals the total number of cells in the battery,

$$N = PS,$$

or

$$P = \frac{N}{S},$$

$\therefore$

$$A = \frac{Se}{\frac{Sb}{P} + R} = \frac{Se}{\frac{S^2b}{N} + R},$$

and it can be shown that the value of S which makes the external current A a maximum is the value of S which also makes $\frac{S^2b}{N} = R$.

Consequently we see that in order to get the greatest current (A) through a given external resistance (R), the cells must be so connected as to make the total internal battery resistance (B) equal to the total external circuit resistance.

The number of cells to be placed in a series to effect this is

$$S = \sqrt{\frac{NR}{b}},$$

when the number of parallels will be

$$P=\frac{N}{S}=\frac{N}{\sqrt{\frac{NR}{b}}}=\sqrt{\frac{Nb}{R}}.$$

These considerations show us that it is actually necessary to have a large internal resistance when the resistance of the external circuit is large in order to obtain the best result.

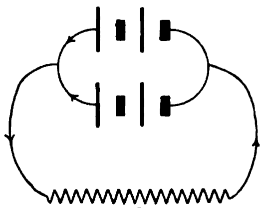


FIG. 252.—Battery of Cells in Series-Parallel Combination.

We may next consider with advantage the distinction between the E.M.F. (E) of a current generator and the P.D. (V) at its terminals. By applying Ohm's Law to any circuit whatsoever, we see that, for a steady current, each unit length of the circuit, whether inside the generator or outside it in the external circuit, must have a perfectly definite P.D. across it. The sum of these P.D.'s across the total number of unit lengths composing the whole circuit, *i.e.* from any point, completely round the whole circuit, back to this same point again, is the total E.M.F. of the circuit, and hence of the generator, which alone produces it.

Now let v be the fall of potential inside the generator between its two terminals, and let V be that round the external circuit outside the generator. Then obviously

$$E=V+v.$$

But by Ohm's Law $\quad v=Ab$ and $V=AR$,

$\therefore \quad E=AR+Ab=A(R+b)$,

and $\quad E=V+Ab.$

Hence $\quad V=E-Ab=\frac{R}{R+b}E.$

E is the E.M.F. of the generator and V its potential difference, while by transposition of the last relation its internal resistance

$$b=\frac{E-V}{A}\text{ ohms.}$$

From these relations we see that the E.M.F. (E) of any generator can be measured by a *high-resistance* voltmeter or galvanometer; for then the current (A) through the latter is very small, and V is practically as large as E, since the product Ab is very small.

Secondary Cells.—The class of appliance coming under this heading is one which, although quite inert in itself, is rendered active by the passage of electric current through it. The electrical energy expended reappears in the form of potential energy of chemical change,

and a redevelopment of electrical energy results from the setting loose of this potential energy by a subsequent chemical reaction or *secondary* chemical change. A secondary cell, accumulator, or storage cell, as it is variously termed, is therefore an electro-chemical transformer of energy. The chief difference between it and a primary cell is that in the latter the elements are active in themselves and require no current to cause them to develop electrical energy by chemical decomposition. Further, when the original constituents of a primary cell are decomposed, a fresh supply must be obtained, whereas those of a secondary cell are *re-formed* by the passage of a current in the opposite direction to that which the cell develops.

The phenomenon of the redevelopment of electrical energy resulting from chemical changes produced by a current can be traced back to having been noticed by Gautherot in 1801. Nothing, however, of much importance resulted from this until 1860, when M. Gaston Planté made the discovery that the arrangement which gave the best results consisted initially of two ordinary lead plates dipping into a dilute solution of sulphuric acid and water. On sending current for a short time through such a cell, the plate at which the current entered turned brown, due to the combination of the oxygen gas produced at its surface with the lead of the plate to form lead peroxide (PbO_2). Hydrogen gas was liberated at the other plate, but no chemical action resulted there. The proportion of electrical energy developed (*i.e.* the discharge) to that put in (*i.e.* the charge) was greater with this cell than any previous one. The long and costly process of making a cell with a reasonable output capacity by Planté's method, however, caused M. Camille A. Faure in 1880 to suggest pasting the lead plates with certain easily reducible oxides of lead, thus enabling a cell with a large capacity to be made in far less time and more cheaply. Faure's suggestion seems to have been a real incentive to research, for since then competition has been keen to discover the best secondary cell. Secondary cells at the present time may be classified as follows :—

1. Those in which the active material is formed from the substance of the plate itself, either by direct chemical or electro-chemical means, and which are known as *Planté* or *unpasted cells.*
2. Those in which the active material is formed from some easily reducible lead salt applied to the plate, and which are known as *Faure* or *pasted cells.*
3. Those which are neither wholly Planté nor Faure cells, but which employ Planté elements for one pole and Faure elements for the other.

Up to the present, many hundreds of patents have been taken out

for secondary cells in one or another of the above classes, but in the following pages we can only consider some prominent instances of the few which have attained commercial success.

Desiderata in a Secondary Cell:—

1. The containing vessel should be of the right shape and size for the volume of plate immersed.
2. The solution should have the right density and be of the requisite purity.
3. The plates should be mechanically strong.
4. They should have no tendency to warp or buckle.
5. If of the pasted type, the paste should be so held in as to be unable to drop out in pellets or cakes.
6. The cell should be capable of the highest rates of charge and discharge without injurious results.
7. For portable and traction work, the cell should be both small and light for a given capacity, and the efficiency should be high.
8. The cost of manufacture, and, above all, that of maintenance, should be small, while the life should be well over five years.
9. The E.M.F. should be large and the internal resistance small, while both should vary little within the usual limits of discharge and atmospheric temperatures met with.
10. As much of the active material on the plates as possible should be exposed to the action of the solution, and for this reason the plates should be as porous as possible, while the solution should preferably be able to circulate around them.

It is needless to say that no cell existent satisfies all these conditions, but research is still rife with a view to devising a cell which does. The ordinary secondary cell which is now so commonly met with is one employing lead with lead salts and sulphuric acid, and when occasion arises we shall speak of it as the *lead sulphuric acid* cell. There are, however, other kinds of secondary cell not employing these materials, and one at least of these we shall have occasion to deal with.

Before going into the construction of modern secondary cells, it may be well to consider the action common to such. In the simple lead cell mentioned on page 411, all the hydrogen gas and most of the oxygen liberated at the plates rise to the surface and escape almost directly the current is started. This is owing to the small surface of lead exposed to the solution, consequent on the want of porosity of ordinary sheet-lead. The hydrogen evolved at the cathode, or plate at which the current leaves the cell, acts in no way on it; and only a little of the oxygen evolved at the anode, or

plate at which the current enters the cell, combines chemically with the surface lead of the anode to form lead peroxide or lead dioxide (PbO_2). The water in the solution, which is thus gradually decomposed into oxygen and hydrogen, slowly disappears, and the solution becomes more strongly acid.

In modern cells of the Planté type, means, which will presently be considered, are adopted to make both the anode and cathode plates porous for quite an appreciable depth from the surface before immersion in the dilute sulphuric acid solution. The effect on sending a current through a cell with such porous plates, *i.e.* charging it, is that practically no oxygen gas is evolved at the anode for some time after commencing the charge, it being all used up in the formation of PbO_2 with the porous surface of the lead. The cathode remains in the condition of spongy porous lead, and when both plates evolve gas quite freely the cell is said to be charged, for then no more oxygen is being absorbed to form PbO_2. In the case of pasted cells the anode or $+^{ve}$ plate is usually pasted with a stiff paste of red lead, *i.e.* minium (Pb_3O_4), and dilute sulphuric acid, the result of the mixing being a formation of lead sulphate ($PbSO_4$). The cathode or $-^{ve}$ plate is pasted with a mixture of litharge, *i.e.* lead monoxide (PbO), and dilute sulphuric acid, which also forms lead sulphate ($PbSO_4$). The composition of the pastes is varied slightly by the addition of other substances, but in the majority of cases is that mentioned above. After the plates are pasted they are allowed to dry or *harden*, and are then *formed* in a bath of dilute sulphuric acid by the passage of electric current.

The chemical action taking place during this forming process may be represented thus :—

$$\underset{\substack{\text{Lead}\\\text{Sulphate.}}}{\overset{(+\text{Plate})}{PbSO_4}} + \underset{\substack{\text{Sulphuric}\\\text{Acid.}}}{\overset{(\text{Solution})}{H_2SO_4}} + \underset{\text{Water.}}{2H_2O} + \underset{\substack{\text{Lead}\\\text{Sulphate.}}}{\overset{(-\text{Plate})}{PbSO_4}} = \underset{\substack{\text{Lead}\\\text{Peroxide.}}}{\overset{(+\text{Plate})}{PbO_2}} + \underset{\substack{\text{Sulphuric}\\\text{Acid.}}}{\overset{(\text{Solution})}{3H_2SO_4}} + \underset{\substack{\text{Spongy}\\\text{Lead.}}}{\overset{(-\text{Plate}).}{Pb.}}$$

Thus it will be seen that the $+^{ve}$ plate exchanges its SO_4 for two atoms of oxygen, while the $-^{ve}$ plate loses its SO_4 altogether. The two molecules of SO_4 decompose the two of water, combining with the hydrogen to form two of sulphuric acid, while the two atoms of oxygen thus freed combine with the lead of the $+^{ve}$ plate to form PbO_2. On discharge, exactly the reverse action takes place, or

$$PbO_2 + 3H_2SO_4 + Pb = PbSO_4 + H_2SO_4 + 2H_2O + PbSO_4,$$

from which it will be seen that both $+^{ve}$ and $-^{ve}$ plates *sulphate*, and that water is simultaneously formed. This action also takes place very

slowly while the cell is allowed to remain idle. Thus, on charging, the solution becomes more strongly acid, *i.e.* its density increases, while on discharging it becomes weaker, *i.e.* its density diminishes. The above relations represent the reactions which occur in *all forms* of lead sulphuric acid cells, whether pasted or non-pasted, during charge and discharge. The ultimate formation of the plates is thus always the same, no matter what the type or make of cell may be, but the action goes on to a very small depth from the surface. The amount of active material PbO_2 on the $+^{ve}$ and Pb (spongy lead) on the $-^{ve}$ is always small compared with the volume of plate. The plates are always easily distinguished: for the $+^{ve}$ one, containing the PbO_2, has a dark brown chocolate colour; the $-^{ve}$ plate, of spongy lead, a slate-grey colour.

The gradual loss of charge in a secondary cell during rest is, according to Messrs. Gladstone and Tribe, due to the frittering away of stored energy by local action between the lead of the plate and the PbO_2 adhering to it, which is in a finely divided state. The peroxide and its lead backing slowly decomposes the acid, producing $PbSO_4$, the action being similar to the local action (p. 394) met with in primary cells. This sulphating or local action of the $+^{ve}$ plate will go on more rapidly when the elements employed have a large metallic surface with but a thin coating or formation of peroxide.

The advantage of the pasted over the non-pasted type lies in the saving of energy and time required in *forming* the plates, and consequently of expense in manufacture, while at the same time increasing the capacity by increase of porosity, and hence of active material bathed by solution. Various expedients have been resorted to in order to effect the above results with non-pasted or Planté cells. The lead plates are corrugated or ribbed by being passed under suitable rollers, or they are cast in moulds closely ribbed, or they are built up of thin laminæ which may be perforated. Plates thus formed mechanically so as to present an increased surface are next subjected to a pickling process consisting in immersing them for some hours in a bath containing a mixture of sulphuric and nitric acids, which eats into the plate and produces porosity. Another method which has been tried is to alloy the lead with some 4 per cent or more of zinc or other suitable metal, which could be eliminated afterwards by electrolysis, leaving the lead in a porous condition.

Epstein suggested boiling the plates in a 1 per cent solution of nitric acid and water, and removing them when a sufficient deposit of lead salt was formed. In the subsequent electrolysing process the lead salts were eliminated, and the porosity thus acquired allowed

of a considerable formation of lead peroxide and spongy lead. In another method the elements are rendered active by a combined depositing and oxidising action effected by electrolysis in an alkaline bath of nitrates composed of 10 parts by weight of water, 2 of sulphuric acid, and 1 of alkaline nitrate (of ammonia, soda, or potash, etc.). The current produces lead nitrate, which is chemically converted into $PbSO_4$, and finally into PbO_2. Further, it is found that the process is greatly hastened by the introduction of large volumes of air into the bath. Of secondary cells formed throughout on Planté principles there are now no prominent commercial examples. There is, however, more than one instance of the latter in which a Planté $+^{ve}$ plate is used with a pasted $-^{ve}$ plate.

FIG. 253.—Positive Plate of D.P. Cell (Strip Type).

The D.P. Secondary Cell.—The so-called D.P. cell made by the D.P. Battery Company, of London, is a familiar example of the kind. The $+^{ve}$ plate in the earlier form of cell still made consists of thin strips (about $\frac{3}{8}$ in. to $\frac{1}{2}$ in. wide) of sheet-lead, laid one upon the other, like the leaves of a book, and all their opposite ends burnt on to two vertical solid lead bars. These, therefore, hold the strips in position, and one of them forms the connecting lug of the plate, as shown in Fig. 253. The $+^{ve}$ plate now used in the D.P. cell, known as the Lumford type, in accordance with the latest Continental practice, is highly grooved or ribbed, being cast as a whole in suitably carved moulds, and having the appearance shown complete in Fig. 258 and also in section in Fig. 257. The $+^{ve}$ plate is formed by a combined oxidising and depositing process similar to that last mentioned. The $-^{ve}$ plate consists of a cast-lead grid of special form (Fig. 254) for keying in the paste on both sides, and is shown complete in Fig. 255.

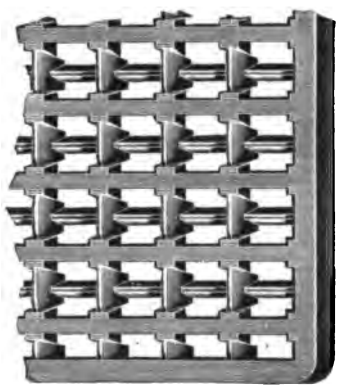


FIG. 254.—Enlarged Section of Negative Grid of Strip-Type Cell.

The vertical projecting lug on each plate is for burning on to lead cross-bars, and the construction of a complete cell will be understood from a reference to Fig. 256, showing two of this type erected on a shelf or stand.

FIG. 255.—Negative Grid complete.

The glass containing-box of the cell rests on four insulators, and carries inside, at the bottom, a wooden frame well soaked in paraffin wax.

On this frame rest the + ^ve^ and − ^ve^ plates assembled alternately, the alternate series, all of one kind, being burnt on to its respective cross-bar as shown. The plates are kept at about $\frac{3}{8}$ in. to $\frac{1}{2}$ in. apart by separators of glass or ebonite, and are braced together by wooden or ebonite tie-bars held by the double-ended metal I frames.

In this and all other types of secondary cell there is one more − ^ve^ than + ^ve^ plate, so that a − ^ve^ plate terminates the series at either end, and each + ^ve^ plate is acted upon on both sides, which is the

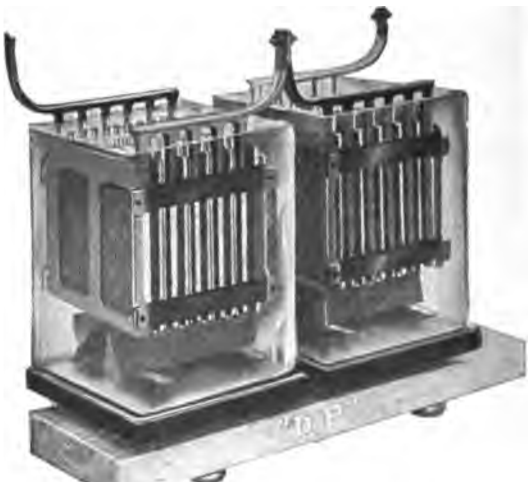


FIG. 256.—Two D.P. Cells complete (Strip Type).

object sought for. The cells shown in Fig. 256 are each 11-plate cells (5 + ^ves^ and 6 − ^ves^), so that the + ^ve^ section is equivalent to one large plate five times the size of any one plate in the cell.

It will also be seen that current flows through ten liquid paths in parallel, each about $\frac{3}{8}$ in. long. From previous remarks we see that the capacity of the cell and its internal resistance vary directly as the number of plates.

The specific gravity of the acid used in this cell is 1·190 (water 1·000), and the Company recommend that the temperature of the battery-room should be kept between the extreme limits 45° F. and 75° F. (*vide* p. 434).

A section of the $-^{ve}$ grid, a complete $-^{ve}$ plate, and a complete cell of the Lumford type (D.P.) are shown in Figs. 259, 260, 261. It will be noticed that in Fig. 261 the plates hang from the rim of the glass box.

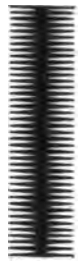


FIG. 257.—Positive Plate (section of Lumford Type).

Monobloc Secondary Cell.—This cell, supplied by Messrs. Drake and Gorham of London, has also a Planté $+^{ve}$ plate combined with a Faure $-^{ve}$ plate. The $+^{ve}$ plate (Fig. 262) is in one block, and consists of thin corrugated sheets of lead punched with holes and assembled one above the other, and cross-tied at all points to give maximum mechanical strength. The channels formed by the punched holes form a casing or receptacle for the negative rods. The $+^{ve}$ block is formed in much the same way as the $+^{ve}$ D.P. plates are, the active material (PbO_2) formed in the crevices being securely keyed in position.

FIG. 258.—Positive Plate complete (Lumford Type).

The $-^{ve}$ element is in the form of spongy lead rods (produced from litharge) enclosed in gauze, the active material being pasted on central lead frames, the upper ends of which are burnt on to connecting bars of lead, as shown in Fig. 263. The gauze envelopes are withdrawn from alternate rods in Fig. 263 in order to show the active material (spongy lead) more plainly. A complete cell section, with $-^{ve}$ rods in position, is shown in Fig. 264; and for traction work, which the cell is specially intended for, this complete section would be immersed in either an ebonite or lead-lined teak box containing the acid, the plates being insulated from the lead lining.

FIG. 259.—Negative Grid (section of Lumford Type).

Some recent tests have shown a 160-ampere-hour cell to have an

ampere-hour efficiency of 96·4 per cent and a watt-hour efficiency of 72·3 per cent, with a capacity of 5·22 ampere-hours or 9 watt-hours per lb. of plate.

FIG. 260.—Negative Plate complete (Lumford Type).

Tudor Secondary Cell.—This cell has been devised and perfected by Mr. Tudor, and is made by the Tudor Accumulator Company, of London. The +^ve^ plate is the most distinctive feature, and, due to the peculiar way in which it is cast, has a large surface. It is cast complete, as shown in Fig. 266, from nearly pure lead, containing less than 0·1 per cent of impurities, in moulds which are in two halves, corresponding to each side of the plate. The pitch of the teeth, or distance between any two succeeding ridges EF of the +^ve^ plate, is about $2\frac{1}{2}$ mm., the depth of groove EA between ridges 6 mm., and the total thickness of plate $\frac{1}{2}$ in., a section being shown in Fig. 265. The +^ve^ plates are *formed* in dilute sulphuric acid contained in lead-

FIG. 261.—D.P. Lumford Cell complete.

lined teak boxes, the deposit of lead peroxide (PbO_2) being obtained first by alternately charging the cells and leaving them on open circuit; afterwards, by alternately charging and discharging them at frequent

intervals, the discharge becoming heavier as the formation advances.

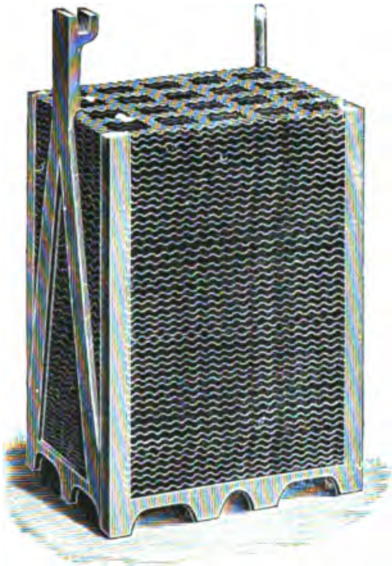


FIG. 262.—Positive Block of Monobloc Cell.

FIG. 263.—Negative Block of Monobloc Cell.

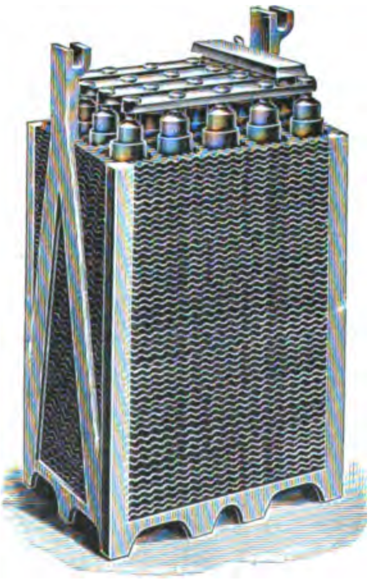


FIG. 264.—Complete Section of Monobloc Cell.

Finally, the cells are charged and discharged under ordinary con-

ditions until they attain their normal capacity, when the plates which have been used as +[ves] in the process are removed and dried. The process lasts continuously for about six weeks, and is effected without the aid of any corrosive acid. The developed surface of the +[ve] plate is large, and is about ten times that of a smooth plate of the same size.

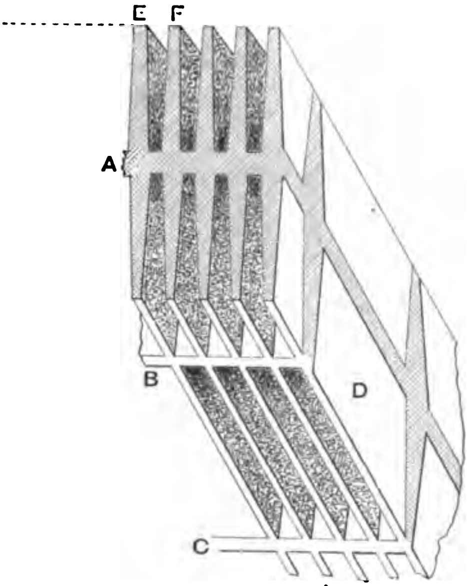


FIG. 265.—Section of Tudor Plate.

The −[ve] plates consist of an *open* grid 0·4 in. thick, cast usually in pure lead, but for certain small accessories and very large negatives an alloy of pure lead with a small percentage of antimony is used for extra rigidity. The bare −[ve] grids are first *pickled*, as it is termed, by coating them electrolytically with a film of PbO_2 in a bath of dilute H_2SO_4 with a heavy current for a few seconds. They are then pasted in the ordinary way with a mixture of litharge and sulphuric acid. After being allowed to dry hard, most of these plates are sent out without further *forming*.

FIG. 266.—Complete Tudor Positive Plate.

The method of mounting the sections inside the containing-boxes, together with the erection of the cells of a battery, is similar to that shown in Fig. 261. When glass boxes are used, the lugs of the plates rest on the rim of the box, and the plates are separated from one another by two or three rows of glass rods $\frac{1}{2}$ in. diameter, as seen, and

held upright by guides cast on the $-^{ve}$ plates. Heavy cells are mounted in lead-lined teak boxes, the plates being supported free of the lead lining by upright glass plates resting on the bottom of the box. The specific gravity of the acid when first put into the cells should be 1·190, and this should rise to about 1·200 when they are fully charged.

FIG. 267.—Tudor Negative Plate.

The maximum E.M.F. at the end of the charge depends on the *rate of charge*, *i.e.* whether a large current has been employed for a short time, or *vice versa*; for the rates specified with the cells it is about 2·62 to 2·67 volts per cell. The makers of this and most other cells allow various rates of discharge, *e.g.* for the 10, 5, 3, and 1 hour rates the lowest limit of voltage to which the cell must discharge is 1·84, 1·82, 1·80, and 1·75 volt respectively. The current in the 1-hour rate being several times that in the 10-hour rate, hence the shorter time taken to discharge the cell to the minimum limit of voltage.

Chloride Secondary Cell.—The manufacture of this well-known cell presents some distinctive features as compared with other types, the origin of the name being due to the use of chloride of lead in the manufacture of the $-^{ve}$ plate, which was the chief feature of the cell.

The $+^{ve}$ plate may be said to be of a specialised Planté type, its manufacture being different from that employed for the $+^{ve}$ plate in other cells. It is constructed in the following way: An alloy consisting of lead and antimony, to ensure rigidity, is run into a mould under an air-pressure of 150 lbs. per square inch, which ensures a homogeneous casting for the framework of the $+^{ve}$ plate.

The moulds are so constructed that this frame is cast with some 124 round holes in it, closely spaced, each hole tapering slightly from opposite sides towards the centre and so forming a double countersinking. Each hole is filled by a rosette of pure lead made by rolling up lead strip or tape which has been gimped or corrugated. The plate is then placed in a hydraulic press and subjected to a pressure of

about 200 tons, which expands the outside faces of the rosettes into the counter-sinking, thereby riveting it into the plate, so to speak. These plates are then *formed* by coupling them up alternately with dummy $-^{ves}$ in a bath of dilute H_2SO_4 and passing a current through until all the interstices of the rosette are filled with a fine adherent hard crystalline coating of lead peroxide (PbO_2). Fig. 268 shows a $+^{ve}$ plate complete, the rosettes being clearly seen protruding slightly from the surface of the frame. The manufacture of the $-^{ve}$ plate is more complex, and entails the separate production of lead chloride in

FIG. 268.—Chloride Storage Battery Company's S Type of Positive Plate.

the first instance. The Company have, however, now ceased to make this form of $-^{ve}$ plate for general work, and supply their so-called exide or pasted $-^{ve}$ with the above $+^{ve}$ plates. A description of the original $-^{ve}$ is instructive, and is as follows.

Known quantities of litharge (PbO) and acetic acid ($C_2H_4O_2$) are well mixed in large dissolving-tanks by mechanical stirrers. The solution of acetate of lead so formed is run into large cisterns and allowed to settle. A sample of the solution is next analysed to find what quantity of hydrochloric acid (HCl) must be added to precipitate all the lead acetate. This addition and the agitation results in the reaction

$$\underset{\text{Lead Acetate.}}{Pb(C_2H_3O_2)_2} + \underset{\text{Hydrochloric Acid.}}{2HCl} = \underset{\text{Lead Chloride.}}{PbCl_2} + \underset{\text{Acetic Acid.}}{2C_2H_4O_2}.$$

The solution is next driven through a filter-press by a steam-pump, the acetic acid emerging from the press in the form of a clear amber fluid, which is used over and over again. The lead chloride, left behind in the shape of large white cakes of paste, is dried in ovens and afterwards mixed with a small percentage of finely divided metallic zinc. This mixture is heated to about 600° C. in brick-lined melting-pots, and becomes as fluid as water. It is then poured by means of plumbago ladles into moulds, which form it into hexagonal pellets with $\frac{1}{2}$-in. sides and two small holes in each. These are next assembled on the plate-moulds, provided with pins at regular intervals, and over which slip the pellets. They are therefore held in position at regular intervals while molten lead is run into the mould under a pressure of 150 lbs. per square inch.

The plates thus cast, and containing the pellets of $PbCl_2$, are next placed alternately with zinc plates in a bath containing a solution of zinc chloride ($ZnCl_2$) and short-circuited, when the following reaction takes place :—

$$PbCl_2 + Zn + ZnCl_2 = 2ZnCl_2 + Pb,$$

the pellets therefore becoming spongy lead. After washing the plates in water, they are connected up with permanent $+^{ve}$ plates in an electrolytic bath of weak H_2SO_4 and charged, the hydrogen gas evolved combining with the last traces of chlorine in the pellets and leaving them in the condition of pure spongy lead. A complete chloride cell can be seen very clearly in Fig. 269.

The Chloride Storage Company now use a separator between the plates, consisting of a thin continuous sheet of wood veneer $\frac{1}{16}$ in. thick supported by two wooden dowels slotted to receive it, and which themselves rest on the bottom of the glass box. The Company now combine their so-called '*exide*' or pasted $-^{ve}$ plate with the $+^{ve}$ plate above described. The specific gravity of the dilute sulphuric acid when first put into the cells should be 1·215.

E.P.S. Cells.—These are representative of the Faure or pasted type of cell throughout, and are so called from being made by the Electrical Power Storage Company, of London. Formed shortly after Faure's discovery, this Company is one of the oldest of its kind, and it has carried out much valuable research in the production of grids for holding the paste. It may truly be said that the grid in a pasted cell is its most vital point, and unless it is constructed so as to hold the paste securely the cell cannot be a commercial success. There are many designs of E.P.S. grids, but space will not permit of their description; suffice it to say that those now in use effect the

desired object to a large extent. The oxides of lead used are substanti-

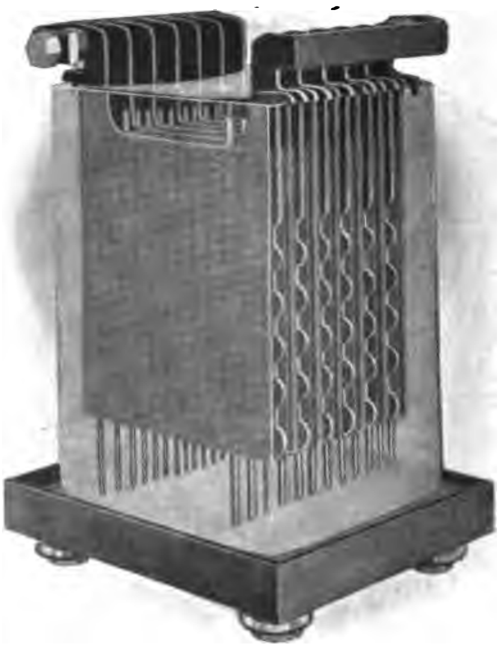
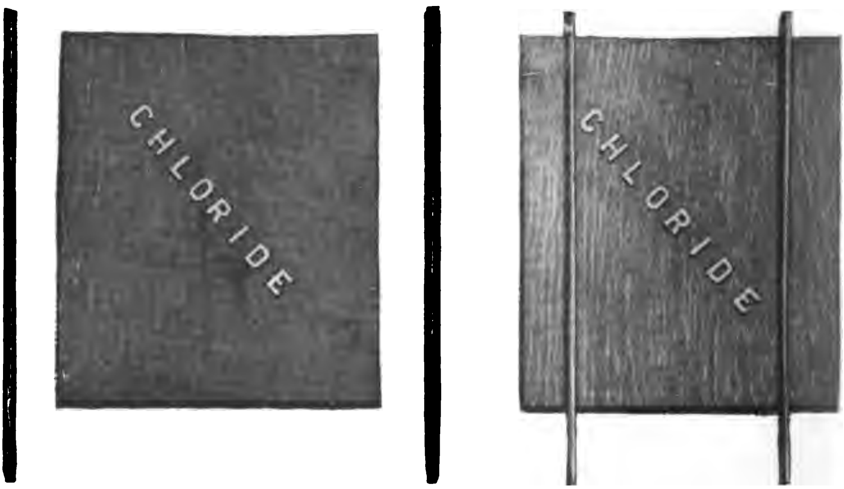


FIG. 269—Complete Chloride Cell, showing Exide Pasted Negative Plate.

ally red lead and litharge for the $+^{ve}$ and $-^{ve}$ plates respectively,



FIGS. 270 and 271.—Chloride Board Separator.

mixed into pastes with dilute sulphuric acid. In some of the many

types of E.P.S. cells, *e.g.* the O.L. and O.K. cells, a Planté $+^{ve}$ plate is employed in certain cases, depending on the work which the cell has to do.

Headland Secondary Cell.—Perhaps one of the most interesting of modern pasted grid cells is that which has been perfected by the Headland Storage Battery Company. The chief feature lies in the form or arrangement of grid, for the pastes employed in the $+^{ve}$ and $-^{ve}$ plates are the same as other makers use.

Fig. 272.—Headland Bar Grid.

The grid consists of bars (Fig. 272) of square section in the form of a four-sided ladder with four thinner pillar-bars bracing the steps of the ladders together inside. As the inner pillars do not touch one another, the bar is hollow from end to end through its centre. It is cast in any length, and a plate built up by burning any desired number of bars to solid lead cross-bars (Fig. 273), a space being left between succeeding bars, as shown.

In pasting the plates, these spaces between bars are cleared out, so that each bar is separated by this gap from the next. Plates of like sign are connected together, as in other makes of cells, by being burnt to lead cross-bars, the $+^{ve}$ and $-^{ve}$ plates being arranged alternately side by side. Each is separated from the next plate by either glass rods, ebonite forks, or sheets of perforated and corrugated ebonite, etc. Fig. 274, shows a 7-plate traction cell with the last-named types of separators and ebonite containing-box on the left.

The advantages of the construction adopted in this cell are, firstly, that there is a free circulation of the electrolyte not only between plates, but also through each plate between bars; secondly, chemical action takes place on all four sides of every bar, thus nearly doubling the effective area of surface of both $+^{ve}$ and $-^{ve}$ plates. Consequently this cell gives a much *greater output* than any other cell for the *same weight, number of plates,* and *area of plane surface.* This is an advantage in traction work, where the dead-weight of the battery has to be carried, of course. Further, the grid when pasted is very rigid, without having a solid core of lead, common to some cells, while the paste is keyed in on four sides.

Edison Alkaline Cell.—In this secondary cell the negative active material consists of finely divided iron, the positive active material of

a finely divided superoxide of nickel, and the electrolyte of a 20 per cent solution of potassic hydrate. On discharge, the iron oxidises, while the nickel oxide is reduced to a lower state of oxidation; but the electrolyte takes no part in the ultimate products of discharge at either electrode, and the quantity required is therefore very small. The active materials are mixed with a nearly equal volume of flake graphite, and moulded under pressure into thin rectangular cakes 3 in. × ½ in. Each cake is enclosed in a very thin sheath of perforated nickelled steel, and they are built up into electrodes by placing a number of them in slots in a thin sheet grid of the same metal and clamping rigidly together in a hydraulic press. The graphite is used to improve the conductivity of the active materials, and takes no part in the chemical reactions of the cell. In a particular cell the normal discharge current per square foot of active element (+ve or −ve plate)

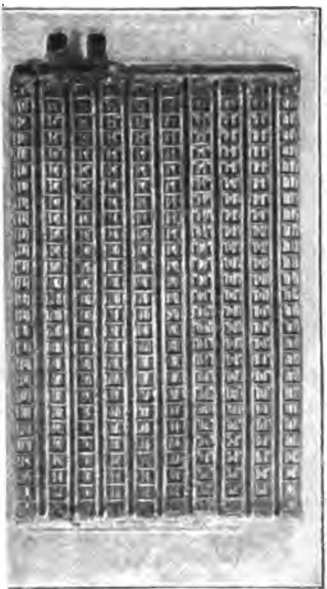


FIG. 273.—Headland Plate Grid.

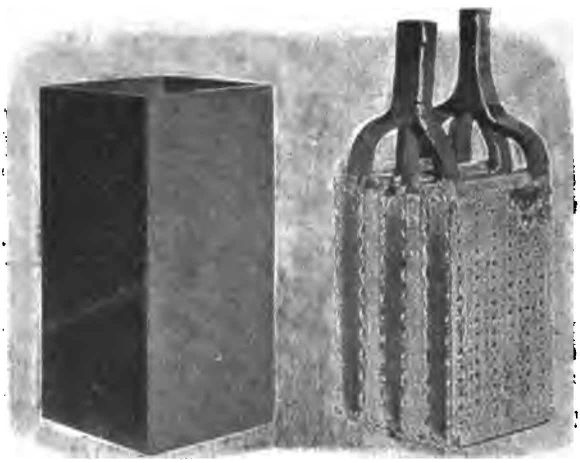


FIG. 274.—Headland Traction Cell.

equals 8·64 amperes; storage capacity per lb. of total cell-weight equals

14 watts; initial terminal voltage, 1·5; mean terminal voltage of full discharge, 1·1 volt.

F. Peters[1] calculates that the cell requires 9 sq. d.cm. of electrode surface per kg. of cell, or 7 sq. ins. per lb., which is about twice as great as in a good lead traction cell; and that twice as many cells would be needed, owing to the mean voltage being only 1·1 volt.

A. L. Marsh suggests that nickel peroxide (N_2O_2) is the real depolarising agent in the cell, and that it is electrolytically reduced on discharge to nickel sesquioxide (Ni_2O_3).

A 28-plate Edison cell was recently tested by E. Hospitalier.[2] It consisted of 14 $+^{ve}$ and 14 $-^{ve}$ plates 2 mm. thick × 12 cm. wide × 23·5 cm. high, and each composed of 24 tablets of compressed active material enclosed in extremely thin perforated and corrugated nickelled-steel cases held in a nickelled-steel grid 0·6 mm. thick. The dimensions of the cell were 13 cm. × 9·2 cm. × 30·2 cm. high, and its total weight 17·09 lbs. Discharged down to 0·75 volt it gave about 153 ampere-hours at 120 amperes, and 170 ampere-hours at 30 mperes. The internal resistance of such a cell rises from about 0·0015 to 0·004 ohm at the end of discharge, and its increase of output with temperature is about 0·26 per cent per degree centigrade.

Apparently the whole of the drop in P.D. during discharge is due to the $+^{ve}$ plate, and for this reason the makers now build a cell with twice as many $+^{ve}$ as there are $-^{ve}$ plates; the $+^{ves}$ being connected in pairs, which considerably increases the output.

A detailed description of the manufacture and performance of these cells made at the Edison Storage Battery Works, Glen Ridge, New York, is given in *Engineering*, 78. pp. 1-5, July 1, 1904. The cells are made in the following sizes:—

TABLE XVII

Type.	No. of Plates. Nickel.	No. of Plates. Iron.	Dimensions.	Normal Capacity (Ampere-Hours).	Maximum Capacity (Ampere-Hours).	Weight in Lbs.
E 18	12	6	$5\frac{1}{8}'' \times 2\frac{21}{32}'' \times 13\frac{1}{4}''$	110	140	$12\frac{1}{2}$
E 27	18	9	$5\frac{1}{8}'' \times 3\frac{13}{16}'' \times 13\frac{1}{4}''$	165	220	$17\frac{1}{4}$
E 45	30	15	$5\frac{1}{2}'' \times 6\frac{9}{32}'' \times 13\frac{1}{2}''$	275	350	28

A. E. Kennelly found the E 18 cell in a particular case to have a quantity efficiency of 58 per cent and an energy efficiency of 45 per cent, while F. M. Davis found the energy efficiency range from 16 per

[1] *Centralblatt Accumulatoren*, 2. pp. 185-188, July 1, 1901.
[2] *Ind. Elect.* 12. pp. 493-497, November 10, 1903.

cent to 62 per cent under a variety of conditions; but no current rate is given, so that these figures must not be taken in too definite a manner.

Effect of Specific Gravity of Solution on E.M.F. of Cell.—The E.M.F. of any lead sulphuric acid secondary cell averages about 2 volts, but it varies with the density of the acid for a charged cell. Other things being exactly the same, the E.M.F. varies from 1·90 to 2·10 volts for a variation of specific gravity of solution from 1·050 to 1·300 respectively. The variation is in the form of a straight line law, *i.e.* 2·00 volts will correspond to 1·175, and so on. We therefore see that between the above limits the E.M.F. of a secondary cell is increased by using an acid solution of greater density. Outside the above limits of specific gravity, the voltage varies much more rapidly than the density.

Variation of Specific Resistance with Density for Sulphuric Acid.—The relation of specific resistance to density in the case of the electrolyte of any cell is important, seeing that the internal resistance of the cell will depend on both. Dilute sulphuric acid behaves in rather an interesting manner with regard to its specific resistance, which is high for large and small densities, and has a minimum value between them. This is indicated by the following figures:—

TABLE XVIII

Percentage of H_2SO_4.	Specific Gravity.	Specific Resistance (Ohms per cm. Cube).	Percentage of H_2SO_4.	Specific Gravity.	Specific Resistance (Ohms per cm. Cube).
1	1006·4	22	30	1223	1·3
5	1032	5	35	1264	1·4
10	1068	2·6	40	1306	1·6
15	1106	1·9	50	1398	1·95
20	1144	1·6	80	1734	9·2
25	1182	1·4	100	1842	

From this we see that the specific gravity of about 1223 (more exactly, 31 per cent, or specific gravity 1231) gives minimum specific resistance or maximum conductivity, and that a 3·5 per cent variation in specific gravity either side does not cause much variation in the specific resistance. Neglecting other effects, it will be seen that the best density to use in a lead secondary cell would be 1220, as this gives minimum resistance of the solution.

Hydrometers.—It is, of course, a necessity to be able to measure the density or specific gravity (sp. gr.) of the solution, and instruments for this purpose are termed *acidometers*, or more commonly *hydrometers*. The measure of sp. gr. is the weight in grammes of 1 c.c. of the solution as compared with that of water at 4° C., its temperature of

maximum density. Water, then, is taken as a standard, and its sp. gr. as 1·000 gramme at 4° C. If 1 c.c. of any other liquid weighs 1·185 grammes, its sp. gr. is said to be 1·185. In practice, the decimal point is omitted, and the last sp. gr. would be called 1185. The range

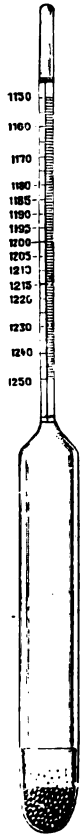


FIG. 275.—Standard Hydrometer.

FIG. 276.—Glass-Bead Hydrometer.

FIG. 277.—Glass-Bead Hydrometer.

in sp. gr. of solutions used for battery acid is from 1150 to 1225 in practice, and hydrometers have to indicate this range.

One of the commonest forms is that shown in Fig. 275, consisting of a flattened tube weighted with shot at the bottom and terminating in a thin stem at the top, in which is sealed the scale. The whole of the flat bulb is always immersed and also the lower part of the stem, so that if the volume of the bulb be large compared with the stem, the scale will be a long open one. The bulb is flattened to $\frac{3}{16}$ in. or $\frac{1}{4}$ in. to enable it to sink between the plates of a cell or in any narrow space.

A *density indicator* rather than a hydrometer proper is shown in Fig. 276, and is called a glass-bead hydrometer. It consists of a flattened tube containing holes at intervals from end to end. It terminates in a hook at the top, and hangs on the side of the cell. The tube contains four glass beads in different-coloured glass and adjusted to float at certain definite sp. grs. Thus the density of the acid contained in that shown in Fig. 276 lies between 1180 and 1215. When the sp. gr. of the electrolyte in a cell not having a transparent containing-box is required, the glass-bead hydrometer shown in Fig. 277 can be used. The stem is open at the top and bottom only, so that when immersed and the finger held over the top, it can be withdrawn and the sp. gr. noted, for the acid is held in the tube and the beads float so long as the top is closed.

Insulation of Cells.—When dealing with a battery of many cells, as is often the case at the present day, the voltage across the terminals

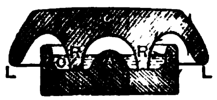


FIG. 278.—Section of Mushroom Oil-Insulator.

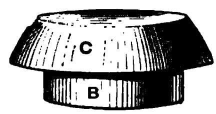


FIG. 279.—Complete Mushroom Oil-Insulator.

is often very considerable. Unless, therefore, the cells are insulated from earth or the stands on which they rest and also from one another, leakage of current may take place from the plates of any cell down the outside of the containing-box and complete its path back to some other point of the battery *via* earth or fixings, etc., and the battery would gradually *run down* and become discharged. In order to avoid this, nearly all makers erect the boxes, when of glass, on wooden trays containing a little sawdust, the object of which is to absorb any moisture that may creep down the outside of the box. The trays rest on what are commonly termed mushroom oil-insulators (Figs. 278 and 279), consisting of a glass base B having an outer rim *r* and central knob A, so that an annular channel is formed between A and *r*, which contains a heavy non-evaporative oil O such as resin oil. The glass cap C is provided with an outer lip L and an inner rim R R, so that R R encircles a hole, and an annular channel is formed between L and R.

Any leakage of current from the cell to earth will therefore take the path from the summit of C to the bottom of B indicated by the arrows. As a portion of this is across the oil O, an enormous resistance is interposed by this oil, and hence the leakage is almost entirely avoided. The chief cause tending to produce leakage is the acid

moisture or spray deposited over everything in the neighbourhood of a battery that is nearly charged and therefore *gassing*. Three or four of these insulators are used under each tray; but lead-lined wooden boxes are placed directly on simple strengthening boards which rest on the insulators, no trays being used. Glass boxes are liable to fracture if they rest directly on the insulators.

Variation of Terminal P.D. with Time of Charge and Discharge.—Quite recently the author made an extensive series of tests, lasting for several months (day and night), on some large secondary cells having Planté $+^{ve}$ and Faure or pasted $-^{ve}$ plates, and weighing 135 lbs. complete with acid each. The cells were of a well-known and prominent present-day type, and were intended for electric lighting and like purposes. Some of the results are embodied in the curves,

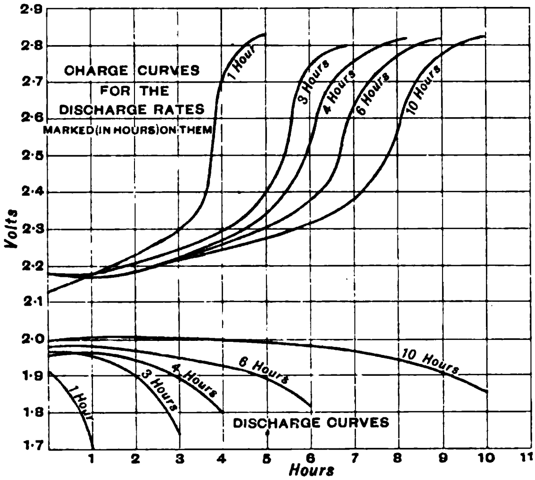


FIG. 280.—Charge and Discharge Curves of a Secondary Cell—Planté $+^{ve}$, pasted $-^{ve}$.

Fig. 280, which show the variation of terminal voltage with time after the cells had reached a perfectly steady condition, as indicated by all the readings falling on the curves on successive charges and discharges. All the charge curves were obtained with a *constant* normal charging current of 32 amperes.

The discharge curves were all obtained with their own particular *constant* discharge currents, namely, 29, 42·5, 50, 70, and 134 amperes for the 10, 6, 4, 3, and 1 hour rates respectively. The 10-hour rate was the normal one, and it should be noted that the 1-hour rate discharge is plotted to a time-scale three times larger than it should be, *i.e.* it should slope from 1·91 volt to 1 on the hour-scale. The charge curves rise more steeply from nearly the same point, 2·18

volts, as the rate of discharge increases, and terminate when the voltage ceases to rise. The discharge curves slope more steeply as the rate of discharge in amperes increases, and the curve at normal rate has a region of constant terminal voltage of about 2 volts for the first 6½ hours of the discharge. The lowest limit of voltage to which the cells were allowed to discharge was 1·85, 1·80, 1·80, 1·75, and 1·70 for the above rates respectively, but notwithstanding this all the charge curves start at about the same P.D. A summary of the results is given in the following table:—

TABLE XIX

Discharge.			Ampere-Hours.		Watt-Hours.		Efficiency.	
Rate in Hours.	Limit in Volts.	Current in Amps.	Input.	Output.	Input.	Output.	(Ampere-Hour) Quantity.	(Watt-Hour) Energy.
10	1·85	29	318	290	764	574	91·2	75·1
6	1·80	42·5	288	255	730	494	88·5	67·7
4	1·80[1]	50	224	200	517	385	89·3	74·5
3	1·75	70	256	220	630	402	85·9	63·8
1	1·70	134	168	134	414	247	80·0	59·7

Effect of Charging Rate on the Discharge.—Another series of tests was subsequently undertaken on the same cells in order to determine the effect on the discharge curves of varying the rate of charge. The incentive for making these tests was the enormous convenience derived from being at times able to charge at a greater current for a *shorter* time, and yet obtain subsequently a good discharge. The results are shown in Fig. 281, the curves denoting the effect when the cells had reached a perfectly steady condition. From them it will be at once seen that practically the same discharge curve and output is obtained from the cells irrespective of the magnitude of the charging current either side of its normal value. It should be remembered that the prior treatment of a cell affects the shape of the subsequent charge and discharge curves, *i.e.* the input and output. It is therefore only possible to obtain results which repeat themselves by following a definite method or cycle of testing. Moreover, there can be little doubt that repeated charging at higher current rates than the normal will seriously shorten the useful life of most cells.

Capacity and Output.—On account of the low internal resistance of secondary cells, the only limit to the current which they will give

[1] This should have been about 1·77 volt, and accounts for the efficiencies at this rate being disproportionate to the rest.

is the resistance of circuit connected to their terminals, and the ability of the plates to stand the flow of a heavy current. For this reason, a short-circuit of low resistance may ruin the cells by reason of the heavy current developed, and, if it does not actually melt the plates, will probably buckle them and dislodge active material. The current which should be taken from and put into the cell is determined by the type of cell and total area of the $+^{ve}$ section, reckoning both sides of a plate; being spoken of as so many amperes per square foot of $+^{ve}$ plate. In the various types of cells now on the market the figure ranges from 4 to about 25 amperes per square foot of $+^{ve}$.

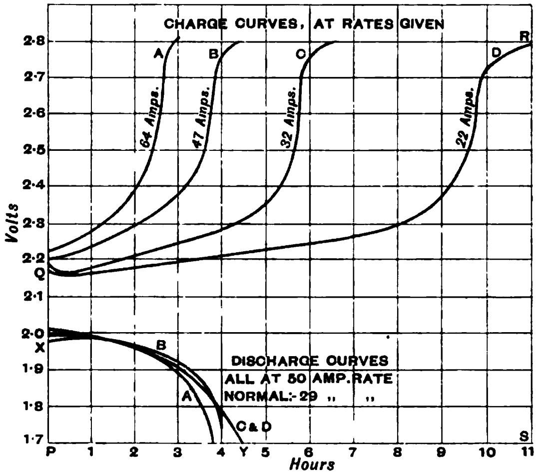


FIG. 281.—Effect of Charging Rate on the Discharge.

The charging current is often set at from 4 to 7 amperes per square foot of $+^{ve}$ plate.

The capacity of any cell for doing useful work, or, what is the same thing, its rated output, is for traction and portable purposes reckoned respectively in either *ampere-hours* or *watt-hours, at a certain current* rate, with a *certain minimum terminal voltage* either *per lb. of plates* or *per lb. of cell complete* with acid. For stationary purposes, questions of weight are omitted. Thus the cells on which the tests just mentioned were carried out were found to have a capacity or quantity output of 290, 255, 200, 210, and 134 ampere-hours, or one of 574, 494, 385, 402, and 247 watt-hours, when discharging to the several limits of voltage at the various currents corresponding to the times given in Fig. 280. The output of energy in watt-hours is, of course, obtained by integrating the area of the discharge curves by means of a planimeter, seeing that the fall of voltage is not uniform,

and therefore that its mean value multiplied by ampere-hours would not give the true watt-hours. The same thing applies to the charge curves. L. Jamau[1] finds that the density of acid used should be greater the higher the rate of discharge, and, further, that the $-^{ve}$ plates should have a greater area than the $+^{ve}$ plates to give the best results and maximum capacity.

Efficiency.—This is the *ratio of output to input* between the lowest *voltage limit of discharge* and highest *voltage limit of charge*, and *at a given current rate*. Without these provisos, the efficiency is meaningless. We therefore have

$$\text{Quantity efficiency} = \frac{\text{ampere-hours given out}}{\text{ampere-hours put in}},$$

which may be as high as 96 per cent when the current density (amperes per square foot of $+^{ve}$ plate) is low. In the above tests it falls from 91·2 at the 10-hour rate to 83·7 at the 1-hour rate, corresponding with a higher current density at the plates. We also have

$$\text{Energy efficiency} = \frac{\text{watt-hours given out}}{\text{watt-hours put in}},$$

and this in actual practice may be anything from 60 to 80 per cent. In the above tests it falls from 75·1 per cent at the 10-hour rate to 59·7 at the 1-hour rate, which shows how increase of current density at the plates decreases the energy efficiency.

Variation of Output with Temperature.—The effect of temperature on the capacity of a secondary cell is far from being unimportant. The reader must, however, be careful not to confuse it with the temperature coefficient of E.M.F. of the cell, which is quite a different thing, meaning the rate of change of E.M.F. with temperature—an almost negligibly small quantity.

The output of a secondary cell increases with increase of temperature, and *vice versa*; an increase making both input and output curves slope more gradually, while of course lengthening the time of both to the usual limits. Heim[2] has shown that in the case of a commercial cell giving an output of 71 ampere-hours at 14° C. and a 20-ampere rate of discharge with a 1·8-volt limit, the output rose to 128 ampere-hours at 45° C., *i.e.* an increase of about 80 per cent. At a 32-ampere rate of discharge this same cell gave an increased output of from 53 ampere-hours at 14° C. to 112 ampere-hours at 45° C., or an increase of 111 per cent.

C. Liagre[3] has shown that between 15° C. and 45° C., and with dis-

[1] *Écl. Électr.* 18. pp. 201-203, 1899.

[2] *The Electrician*, vol. 48. p. 55, November 1, 1901.

[3] *L'Éclairage Électrique*, vol. 29. p. 150, November 2, 1901.

charge rates varying from 25 to 180 amperes, the rate of increase of output is the same for any current and is uniform, the mean rate of increase being about 2·7 ampere-hours per degree Centigrade. Seeing that the range of temperature met with in this country throughout the year lies between about $-3°$ C. and $20°$ C., it would seem imperative for battery-makers to specify the temperature at which they guarantee the particular output, for within this range it is possible to have a variation of output amounting to from 50 to 90 per cent.

Effect of Method of Charging on the Output and Efficiency.—To some extent the curves of Figs. 280 and 281 indicate this when the charge and discharge are effected at *constant current*. Messrs. Cohen and Donaldson[1] have, however, investigated the effect on a *constant-current discharge* of *charging at constant P.D.*, and find that this considerably increases the output (by some 25 per cent in the cell tested). The cell was of a 5-plate Tudor type, and was listed to be discharged at 36 amperes for 3 hours to a voltage limit of 1·815. The normal charging current was 20 amperes, and the constant P.D. employed in charging was 2·508 volts. At the end of discharge the rush of charging current consequent on applying 2·508 volts to its terminals was about 105 amperes, and this dropped to 10 amperes in 80 minutes.

The energy efficiencies obtained with constant P.D. and constant current-charging methods were 70·5 and 81 per cent respectively, while the quantity efficiencies were 93·5 and 95·5 per cent. These results show that, while the output is increased some 30 per cent, the efficiency is diminished by charging at constant P.D., and a very material saving of over 50 per cent in time is effected. On the other hand, only certain types of cells having strong plates could possibly stand the heavy rush of current in this method, and it is only reasonable to suppose that the life would be seriously diminished.

Treatment and Ailments of Secondary Cells.—These are of far-reaching importance to users of such cells, for their initial cost is considerable, and therefore a long life is highly desirable. Within limits, the life is practically dependent on the treatment and attention given to them, and if this is of the best, then the life of course depends on the total number of ampere-hours taken out. The user will be well repaid for careful attention and trouble taken for their efficient maintenance, which embraces such matters as the following: The level of the solution should always be kept about half an inch above the plates, and, as the liquid evaporates and disappears through spraying, more *distilled water*, which should always be used, or dilute sulphuric acid, should be added, as the case may require,

[1] *The Electrician*, vol. 41. p. 674, September 16, 1898.

in order to maintain the sp. gr. constant in the cell *say when fully charged.*

Cells should never be discharged below 1·80 volt per cell, and should never be allowed to remain in this discharged condition for many hours. Inattention to these two points in particular will result in the formation of a *hard, non-conducting* form of lead sulphate on the plates which is very difficult to get rid of even by repeated charging afterwards. Even if it is got rid of, it will usually scale off the plates, bringing some of the active material with it. This is often a cause of trouble, for the scale is usually able to bridge the narrow liquid gap between two plates, and then forms an internal short-circuit which gradually runs down the cell whether it be on open circuit or otherwise. In such cases a rod of some non-metallic material such as glass or ebonite should be moved sideways across the plates to dislodge the scale and send it to the bottom. A bad short-circuit having a very low resistance may do more harm to a cell than weeks of regular use.

L. Jamau, in a paper[1] on the sulphating of plates, points out the increase in the rate of formation of sulphate caused by even a small percentage of antimony (under 1 per cent) alloyed with the lead, especially with acid of high density. He recommends either pure lead for the $+^{ve}$ plates or a low density of acid.

Buckling or warping of the plates takes place with too heavy a charge or discharge, and also when the cell is allowed to rest in a discharged condition, no matter how strong the plates are or what the type of cell. It is supposed to be due to unequal expansion of the paste on opposite sides of the plate. This effect is particularly disastrous to some types of pasted plates, causing the paste to drop out in pellets, etc. When this happens, the plates should be removed and straightened. The solution of a cell which has reached a fully charged condition appears in a state of ebullition which is technically known as *boiling* or being milky. This is due to the bubbles of gas which cannot any longer be taken up in the reduction and formation process permeating the whole of the solution. They rise to the surface and burst, causing a fine spray of acid vapour to be evolved. Much of the spray, however, is deposited on the under side of glass-plate *spray-arresters* which are placed over the top of the cell, and runs back into the solution. Some, however, permeates the room, which should therefore be *well ventilated* and have as little metal-work in its construction as possible, so as to be unaffected by the active atmosphere.

[1] *Écl. Électr.* 16. pp. 133-136, 1898.

The best connection between the + ^{ve} pole of one cell and the − ^{ve} of the next is made by burning the two lead lugs together, the joint being totally unaffected by the acid spray. When brass or copper bolts are used to clamp the lugs together they corrode and become a great nuisance. Quite recently a special lead-covered brass bolt has been brought out (Fig. 282) which overcomes this difficulty.

The purity of the dilute sulphuric acid solution is a matter of great importance. The commoner impurities to be looked for are non-volatile mineral matter such as calcium and lead sulphates, alumina and silicic acid, iron, hydrochloric acid, arsenic, nitric and nitrous acids, and sulphurous acid. Of the rarer impurities, the solution should

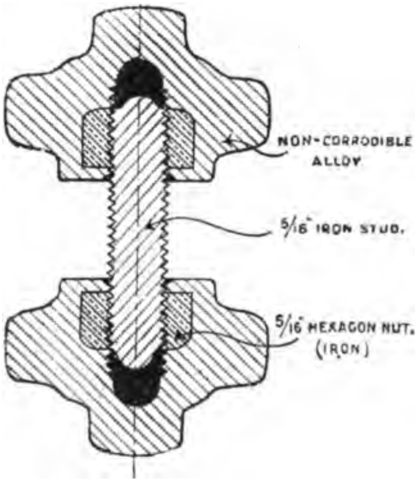


FIG. 282.—Lead-Capped Bolt.

be *free* from organic matter, and should not contain more than 0·001 gramme per 100 c.c. of manganese, chromium, copper, or zinc. It should be free from arsenic, nitrous, nitric, and sulphurous acids, and not contain more than 0·001 gramme of HCl, 0·002 gramme of iron, or 0·05 gramme of non-volatile matter each per 100 c.c. in acid of sp. gr. 1215.[1] The commercial article known as brimstone sulphuric acid is usually freest from the foregoing impurities. It is best to use distilled water, but clean rain-water in the country may often be used instead. When the plates of a cell are badly sulphated, *i.e.* coated with a white-looking scale of hard lead sulphate, this can be removed by repeated charges and discharges.

[1] See Paper on 'Secondary Cells: Their Deterioration and the Causes,' read by the author before the Leeds Local Section of the Institution of Electrical Engineers, December 13, 1905.

Uses of Secondary Cells.—Many are the uses to which this type of cell can be put, for it is capable of responding instantaneously to all reasonable demands for electrical energy. Secondary batteries are used in conjunction with running engine-dynamo sets to supply sudden temporary overloads which would otherwise put an abnormal strain on the running plant. In this capacity they also act as pressure regulators, and discharge in parallel with the dynamos at times of heavy load. A battery enables the dynamos to be stopped about 11 P.M., and from then supplies the necessary power for the night if installed in suitable capacity. The prime cost and depreciation of a battery for a given kilowatt output (say for 5 hours) is about the same as for a steam-engine-dynamo-boiler set for the same period, but the running cost is reduced by the use of a battery, seeing that it will take temporary overloads for which extra running plant would otherwise have to be supplied under wasteful conditions.

QUESTIONS ON CHAPTER X

[*Supplement all Answers with Sketches when possible.*]

1. Describe the Clark standard cell, and state what precautions are required in its use. (C. and G. Ord. T. and T. 1897.)

2. What forms of battery cells are used in practical telegraphy? What is the E.M.F. of each, and what special advantages does each possess? (C. and G. Ord. T. and T. 1897.)

3. Describe the construction of a Léclanché cell, and state what are its advantages and disadvantages. Under what circumstances would you employ Léclanché cells (Prelim. C. and G. 1897.)

4. Describe in detail the construction of a Clark standard cell. (Hons. Sect. I. C. and G. 1897.)

5. The liquid in all the cells in a battery of accumulators has the right density after charging, but one of the cells, although of the same size as the others, has a much smaller capacity: what is the cause, and what remedy would you employ? (Hons. Sect. II. C. and G. 1897.)

6. Describe, with sketches, two well-known types of secondary cells, one suitable for central-station work and one for traction, and point out in what respects they differ. (Ord. C. and G. 1898.)

7. Sketch and describe some good form of accumulator, and explain how you would ascertain whether it was charged or discharged. About how much current may be taken from an accumulator per square foot of +^{ve} plate, and what occurs if the cell be discharged at a much higher rate? (Prelim. C. and G. 1899.)

8. What is the effect upon the storage capacity, the life, and the electrical efficiency respectively, if a constant pressure instead of a constant current be used in charging accumulators? Under what circumstances is the charging at constant pressure particularly useful? (Hons. Sect. II. C. and G. 1899.)

9. The poles of a battery of E.M.F. E are connected by a resistance R; it is found that the current flowing in the circuit is C, and the P.D. between the poles of the battery is e: what is the resistance of the battery (a) in terms of E, R, and C; (b) in terms of E, R, and e? (Ord. T. and T., C. and G. 1900.)

10. In a telegraph battery of the Daniell type, the zinc plate is placed in a solution of zinc sulphate: as such a solution does not, under ordinary conditions, act chemically upon the zinc, how is it that action takes place in the battery? (Ord. T. and T., C. and G. 1900.)

11. Describe any form of battery especially suitable for telephonic purposes, and state how it can be tested and maintained. (Ord. T. and T., C. and G. 1900.)

12. Two cells A and B, each of 1-volt E.M.F. and of 5 and 10 ohms resistance respectively, have the $+^{ve}$ pole of A joined to the $-^{ve}$ pole of B, and the $-^{ve}$ pole of A joined to the $+^{ve}$ pole of B: what is the P.D. between the respective junctions? (Hons. Teleg., C. and G. 1900.)

13. What is a 'dry battery,' and how does it act? What special advantages does it possess, and what is its approximate E.M.F.? (Hons. Teleg., C. and G. 1900.)

14. A battery of 5 ohms resistance has its poles connected by a resistance of 10 ohms; the P.D. between them is 15 volts: what is the E.M.F. of the battery? (Ord. T. and T., C. and G. 1901.)

15. A battery of 10 cells is connected to two telegraph circuits of 1000 and 2000 ohms resistance: what current passes through each circuit, and what change in these currents will take place if a resistance of 500 ohms is connected across the poles of the battery? (Ord. T. and T., C. and G. 1901.)

16. Describe any form of 'dry' battery, and illustrate the same by a sectional sketch. (Ord. T. and T., C. and G. 1901.)

17. Fully describe the construction of an accumulator; state how it is charged, and what E.M.F. the charging current should have compared with the maximum E.M.F. of the accumulator. How is it known when the latter is fully charged? (Hons. Teleg., C. and G. 1901.)

18. Give examples illustrating the distinctions between the E.M.F. of a current generator and the P.D. between its terminals. (Prelim. C. and G. 1901.)

19. How is an accumulator made, and how is it employed in practice? What are the various precautions that should be adopted in the use of accumulators, and what happens if these are neglected? (Prelim. C. and G. 1901.)

20. Describe any form of accumulator. What is its normal E.M.F., and how would you determine whether it was fully charged or not? (Ord. T. and T., C. and G. 1902.)

21. Describe any form of accumulator. What relation is there between its charge and the density of the acid? Between what limits should the density of the acid be maintained, and in what terms is the working capacity of an accumulator expressed? (Hons. Teleg., C. and G. 1902.)

22. Two dry cells each have an E.M.F. of 1·5 volt and an internal resistance of 0·3 ohm: how would you couple them up so as to give the greatest current through a wire having a resistance of 0·4 ohm, and what would be the value of the current? (Prelim. C. and G. 1903.)

23. What are the qualities required for a good voltaic cell? How may the resistance of a battery be diminished and the E.M.F. increased? (Ord. T. and T., C. and G. 1904.)

24. Describe the Daniell and bichromate cells. If the E.M.F. of a cell be 2 volts and its resistance 4 ohms, what will be the P.D. between its terminals if these are joined by a resistance of 16 ohms? (Hons. Teleg., C. and G. 1904.)

INDEX

Absolute system of units, 59
Absorption, residual, 170
    of light by lamp globes, 382
Acceleration, definition of, 51, 60
Acid, variation of specific resistance with density of sulphuric, 428
    for secondary cells, purity of sulphuric, 437
Acidometers, 428
Air-pump, Fleuss 'Geryk,' 319
    Sprengel, 323
    Barr and Stroud rotatory, 326
    evacuation, liquid, 328
Alkaline secondary cell, Edison's, 425
Allevard steel magnets, 10
Ammeters, soft-iron needle, 227
    vulcan, soft-iron needle, 228
    Crompton moving-coil permanent-magnet, 229
    hot-wire, 232
Ampere, the, 38
    turns, 131
Anode, 37
Apparent power, 269
    resistance of the arc, 349
Arc, voltaic, 345
    the crater, temperature, and form of an electric, 347
    striking an electric, 347
    temperature of an electric, 347
    crater of an electric, 348
    back E.M.F. of the, 349
    length and resistance of the electric, 349
Arc lamp, regulating mechanism, 351
    carbons, rate of consumption, 348
    carbons, diameter of, 349
    differential, 352
    modern, 352
    the Davy enclosed, 353
    compensator for, 354
    silencing device, 354
    Davy twin, 355
    Davy inverted reflecting, 356
    Stewart, 356
    Stewart twin, 357
    Stewart high-economy, 359
Arc light diffusers, 372
Arcs, long and short, 350
    flaring and hissing, 350
    the Gilbert, 360
    focussing, 361
    'Excello' intense-flame, 363
    Bremer, 371
    electrolytic, 373
    magnetite, 373
    Foster's hot-wire-control, 374
    resistances, choking coil, economy coil of, 378
    intensity of an, 382
Astatic galvanometer, Kelvin, 206
Atomic weight, 41, 43
Attraction and repulsion, electrical, 20

B.A. unit of resistance, 44
Balancing coil, 380
Ballistic galvanometers, 40, 168, 209
Bichromate primary cell, 395
Board of Trade unit, the, 58
Board separators for secondary cells, chloride, 424
Brewer arc lamp, 371
Bridge, the Wheatstone, 90
    the metre, 92
    the Post Office pattern Wheatstone, 93
    fault-localising, 95
Buckling of plates in secondary cells, 436
Bulbs, frosting electric glow-lamps, 308
    coloured, 308

Calorie, the, 54
Candle-power, hemispherical, 370
    with diameter of carbon, variation of, 383
Cap of glow-lamp, 304
Capacities, combinations of, 179
Capacity, specific inductive, 25, 29, 168
    unit of, 172
    of condenser and its dimensions, relation between, 172
    of condenser, rules for the, 174
    of electric mains, 176
    and output of secondary cells, 432
Carbon 'Excello' flame arc lamp, 368

Carbons, metal-coated, 346
conductivity of arc lamp, 347
cored arc light, 348
rate of consumption of arc light, 348, 383
Cathode, 37
Cell, bichromate primary, 395
Léclanché primary, 397
dry, 399
the Dania dry, 400
the Daniell, 401
the Clark standard, 402
the Weston standard cadmium, 404
efficiency of secondary, 434
variation of output with temperature in secondary, 434
variation of output with method of charging secondary, 435
buckling of plates in secondary, 436
lead-capped connecting bolt for secondary, 437
Cells, primary, 391
simple voltaic, 393
design and maintenance of primary, 404
predetermination of E.M.F. of primary, 405
methods of grouping, 408
secondary, 410
desiderata in secondary, 412
the D.P. secondary, 415
the monobloc secondary, 417
the Tudor secondary, 418
the chloride secondary, 421
the exide secondary, 423
the E.P.S. secondary, 423
the headland secondary, 425
the Edison secondary, 425
Charge, the electrical, 21
Charging rate on the discharge, effect of, 432
Chemical property of an electric current, 35
equivalent, 41, 43
Chloride secondary cell, 421
Choking coil, 378
Circuit, magnetic, 132
Circuits in series and parallel, 83
Clutch of Gilbert arc lamp, 362
Coefficient of specific resistance, 69
of resistance, temperature, 72
of self-induction, 196
of mutual induction, 199
Coercive force, 12, 145
Coil winding for electro-magnets, 158
length of wire on a given, 160
resistance of a given, 160
weight of a given wire to fill a given, 161
power wasted in and temperature rise of a, 162
and core of electro-magnet, relation of diameter, 162
Compensator for arc lamps, 354, 381
Condenser, an electrical, 168
capacity of a, 168
construction of, 168
action in a, 169
energy and work in charging and discharging a, 179
Condensers, cylindrical, 176
of two-wire non-concentric cables, 177
uses of, 181
Conductance, practical unit of electrical, 46
specific conductivity, 81
Conduction and insulation, electrical, 22 23
Consequent poles, 128
Conservation of energy, the law of the, 58
Coulomb, the, 39
Crater of an electric arc, 347
diameter of arc lamp, 349
Current, the electric, 33
properties of the electric, 35
the magnetic effect of an electric, 35
the heating effect of an electric, 35
the chemical effect of an electric, 35
the physiological effect of an electric, 35
the physical effect of an electric, 36
practical unit of, 38
and magnetic force produced, relation between, 128
Currents, momentary or transient, 40
Cycle of magnetisation, 145

Dania dry cell, output of, 401
Daniell cell, the, 401
D'Arsonval moving-coil galvanometer, 211
Davy enclosed arc lamp, 353
twin arc lamp, 355
inverted reflecting arc lamp, 356
Demand indicator, maximum (Atkinson-Schattner), 261
Density, 49
electric, 24
surface, 25
Diamagnetic substances, 136
Dielectric hysteresis, 171
Dielectrics, 29, 168
table of, 30
Differential arc lamp, 352
Diffusers, arc light, 372
Distribution coil, 380
of illumination from arc lamps, 382
'D.P.' secondary cell, 415
Dry cells, 399
Duddell oscillograph, 217

Economiser of 'Excello' flame arc lamp, 364
Economy arc lamp, high, 359
coils for arc lamps, 378, 381
Eddy currents, 192, 249
Edison secondary cells, 425
Efficiency of electric glow-lamps, optical and commercial, 309

Efficiency of electric glow-lamps, maximum economic, 310, 312
of Nernst electric lamps, 337
of thermo-electric generators, 391
of secondary cells, 434
and output of secondary cells, effect of method of charging on, 435
Electric density, 24
potential, 26
current—its nature and direction of flow, 33
Electrical induction, 28
Electricity, its nature, 20
Electrification, two kinds of, 20
the origin of, 24
Electro-chemical equivalent, 40, 43, 406
Electrodes, choice of arc lamp, 345
Electrodynamic action between conductors, 124
Electrolytes, 37
Electro-magnetic induction, 182
magnetic induction, laws of, 190
Electro-magnets, 151
for alternating currents, 155
lifting power of, 156
uses of, 158
winding of, 158
power wasted in and temperature of, 162
Electromotive force, 49
Electrostatic induction, 167
voltmeters (Ayrton-Mather firm), 237
E.M.F., evaluation of induced, 190
of the arc, back, 349
thermally, the production of, 385
laws of thermo-, 386
with density of acid solution, variation of, 428
Enclosed arc lamp, the Davy, 353, 356
the Stewart, 356
Energy, definition and unit of, 57, 60
kinetic and potential, 57
E.P.S. secondary cells, 423
Equivalents, chemical, 41, 43
electro-chemical, 40, 43
Evacuating glow-lamp bulbs, 303, 319
Evacuation by liquid air, 328
by absorption chemically, 328
degree of, 329
'Excello' intense-flame arc lamp, 363
Exide secondary cells, 423

Farad, the, 172
Faraday's law of electrolysis, 38
law of induction, 191
Fault-localising bridge, 95
Faure secondary cells, 411
Fibre and pivot suspensions, 217
Field of a current in a straight wire, magnetic, 122
of a current in a coiled wire, magnetic, 125
and polarity of a solenoid, magnetic, 126
Filament of glow-lamps (M.F. and mounting), 297
Filaments of glow-lamps, uniformity of, 315
causes of failure of, 315
Flame arc lamp, 'Excello' intense-, 363
Flaring in an electric arc, 350
Flashing process in glow-lamp M.F., 301
Fleuss 'Geryk' air-pump, 319
Flux density, 133
Flux, magnetic, 18, 133
Focussing arc lamp, 361
Foot-pound, the, 53
Force, electro-motive, 49
definition and nature of, 50
unit of, 51, 60
Foster hot-wire-control arc lamp, 374
Foucault or Eddy currents, 192, 249
Frequency indicators (British Westinghouse), 266
Frosting glow-lamp bulbs, 308

Galvanometer, Ballistic, 168, 209
Galvanometers, moving-coil and moving-needle, 204
Post Office bridge form, 204
Kelvin astatic, 206
moving-coil, D'Arsonval, 211
Ayrton and Mather moving-coil, 213
Holden's hot-wire, 214
scale for reflecting, 216
Gauge, vacuum (M'Leod), 329
Geryk air-pump, 319
Gilbert arc lamp, 360
clutch of the, 362
Glass-bead hydrometer, 429
Glow-lamp, Nernst electric, 331
Glow-lamps, the filament of electric, 297
forms of electric, 305
night light or reducing, 306
Aston Bohm, 307
frosting, 308
efficiency of electric, 309
life of electric, 309, 314
filaments, causes of failure of, 315
in fiery mines, 317
silicon carbide, 317
osmium, titanium, and tantalum, 317

Hand rule for direction of magnetic field and current, 123
Headland secondary cell, 425
Heating property of an electric current, 35
Hemispherical candle-power, 370
Henry, the, 198
Hissing of an electric arc, 350
Horse-power, the, 56
Hot-wire-control arc lamp, 374
Hot-wire galvanometer, Holden's, 214
ammeters and voltmeters, 232
Hysteresis, magnetic, 144
static and viscous, 151
dielectric, 171
testing instruments, 287

Hysteresis tester (Blondel-Carpentier), 288
Hydrometers, 428

Idle or wattless current, 269
'Idle-wire' method of damping oscillations, 213
Illumination, distribution of, 382
Impedence coil, 378
Incandescent electric lamps, forms of, 305
night light, 306
frosted and coloured, 308
efficiency of, 309, 312
life of, 309, 314
filaments of, 315
in mines, 317
silicon carbide, 317
osmium, tantalum, etc., 317
Indicator, maximum demand (Atkinson-Schattner), 261
frequency (British Westinghouse), 266
power factor, 268
Induced current, direction of an, 185
currents, measurement of transient or, 167
Induced E.M.F., evaluation of the, 190
current, quantity of electricity in an, 191
Induction, magnetic, 8
density, 18, 133
electrical, 28
electrostatic, 167
electro-magnetic, 182
between parallel straight conductors, 184
between a magnet and coiled circuits, 185
between coiled circuits, 186
self, 194
coefficient of self, 196
practical unit of self, 197
calculation of self, 198
mutual, 199
calculation of mutual, 200
Induction coil, Ruhmkorff, 187
laws of electro-magnetic, 190
Inductive capacity, specific, 29, 168
circuits, forms of, 195
Inductivity, magnetic, 14
Inertia, electrical, 197
Insulating materials, properties of, 105
materials, table of specific resistances of, 107
Insulation and conduction, electrical, 22, 23, 105
resistance, 255
resistance indicator, Everett-Edgcumbe, 256
Insulators for supporting conductors, 111
for supporting conductors, forms of, 114
battery, 430
Integrating wattmeters, 246
Intensity of magnetisation, 16
of arc light, 382
Internal resistance of primary cells, 396-401
Inverse currents, 185
Inverted reflecting arc lamp, Davy, 356

Joule's law, 55

Kelvin astatic galvanometer, 206
Kilowatt-hour, the, 58
Kinetic energy, 57

Lag, magnetic, 150
Lamp bulb, evacuation of, 303
Lamps, electric incandescent, 296
filament of electric glow-lamps, 297
efficiency of electric glow-lamps, 309
in mines, 317
Nernst electric incandescent, 331
efficiency of Nernst electric, 337
vapour, 337
electric arc, 345
electrodes of electric arc, 345
regulating mechanism of arc, 351
differential arc, 352
modern arc, 352
the Davy enclosed arc, 353
the Davy twin arc, 355
the Stewart arc, 356
the Davy inverted reflecting arc, 356
the Stewart twin arc, 357
high-economy arc, 359
Gilbert arc, 360
focussing arc, 361
'Excello' intense-flame arc, 363
electrolytic arc, 373
magnetite arc, 373
Foster's hot-wire-control arc, 374
Law of the conservation of energy, 58
Laws of magnetic attraction and repulsion, 4, 14
of electro-static attraction and repulsion, 21, 25
of magnetic resistance, 136
of the magnetic circuit, 136
of thermo-E.M.F.'s, 386
Leakage, 109
laws of, 110
Léclanché primary cell (bell form), 397
primary cell (agglomerate form), 398
Leyden jar, 182
Life of electric glow-lamps, 309, 314, 316
Lifting power of electro-magnets, 156
Lines of magnetic force, 5, 132
Liquid-air evacuation, 328
Local action in primary cells, 394
Lodestones, 2
Lorenz method of determining unit of resistance, 45
Low resistances, standard known, 102

Magnet, definition and properties of a, 2
characteristics of a, 2
distribution of magnetism in a bar, 3
magnetic axis of a, 3

Magnet, neutral axis of a, 3
the earth a, 4
Magnetic substances, 4
attraction and repulsion, laws of, 4, 14
force, lines of, 5
field, 6
induction, 8, 17
screening, 8, 192
retentivity, 11
saturation, 13
permeability or inductivity, 14, 135
moment of a magnet, 16
pole, unit, 17
flux, 18, 133
property of an electric current, 35
field of a current in a straight wire, 122
field of a current in a coiled wire, 125
field and polarity of a solenoid, 126
force produced, relation between current and, 128
circuit, 132
potential, 134
circuit, laws of the, 136
resistance, laws of the, 136
circuits, open and closed, 139
induction with magnetising force, variation of, 140
permeability with induction, variation of, 143
hysteresis, 144
cycle, 145
lag, 150
testing sets (Drysdale's), 278
permeability balance (Ewing's), 285
hysteresis, instruments for measuring, 287
Magnetisation, intensity of, 16
Magnetising force of a solenoid, 130
force with magnetic induction, variation of, 140
Magnetism, free, 5
molecular theory of, 11
residual, 12
Magnetite, 2, 373
arc lamp, 373
Magneto-motive force, 133
Magnets, permanent, 2, 10
mutual action of, 4
strength of, 10
compound or laminated, 10
tractive force of, 12
electro, 151
for alternating currents, electro-, 155
Mains, capacity of electric, 176
Mass, definition and nature of, 49, 51
Matter, definition and nature of, 49
Maximum demand indicators (Atkinson-Schattner), 261
Mechanism of an arc lamp, regulating, 351
Megohm, the, 46
Mercury-vapour lamps, 337
Meters, electricity supply, 246
Meters, eclipse B.N.R. type, direct-current, electricity supply, 247
Brush-Gutmann alternating-current, electricity supply, 250
Metre bridge, the, 92
Mho, the, 46, 82
Micro-coulomb, the, 40
Microfarad, the, 172
Microhm, the, 46
Milliampere, the, 39
Momentum, 52
Monobloc secondary cells, 417
Mutual induction, coefficient of, 199
induction, calculation of, 200

Negative electricity, 21
Nernst electric incandescent lamp, 331
electric incandescent lamp, efficiency of, 337
Neutral axis of a magnet, 3
point of a thermo-couple, 386, 389

Ohm, the, 45
the Paris, 44
Ohm's Law, 65
Open arc lamp, 353
Oscillograph, Duddell, 217
double high frequency, 219
indicating arrangements of the, 220
properties and uses of the, 221
Output and capacity of secondary cells, 432
with temperature of secondary cells, variation of, 434
of secondary cells, effect of method of charging on, 435
Oxidising or pickling solution for Planté plates, 415

Parallel and series circuits, 83
Paramagnetic substances, 136
Paris legal ohm, 44
P.D. with time of charge, etc., variation of, 431
Peltier effect, the, 387
Permeability, magnetic, 14, 133
balance, Ewing's magnetic, 284
Permeameters, 278
Permeance, 136
Phasemeter (Everett-Edgcumbe), 268
Physical property of an electric current, 36
Physiological property of an electric current, 35
Pickling or oxidising solution for Planté plates, 415
Pivot and fibre suspensions, 216
Planté secondary cells, 411
Polar curve of candle-power, 369
Polarisation in primary cells, 394
Polarity of a magnet, 3
Poles of a magnet, 3
consequent, 128
Positive electricity, 21

Potential, electric, 26, 48
difference of electric, 26, 49
of the earth as zero, 27
difference, practical unit of, 49
or latent energy, 57
magnetic, 133
Potentiometer standard, 222
Poundal, the, 51
Power, definition and unit of, 56
of electro-magnets, lifting, 156
factor indicators, 268
Pressure, electrical, 46
Primary cells, 391
design and maintenance of, 404
predetermination of E.M.F. of, 405
Pump, Fleuss 'Geryk' air-, 319
Sprengel air-, 323
Barr and Stroud's rotatory air-, 326
Pyrometers, electrical, 272

Quadrant, a, 198
Quantity, practical unit of, 39

Reactance coil, 378
Reactions in secondary cells, 413
Recording instruments—ammeters, voltmeters, and wattmeters, etc., 244
Regulating mechanism of an electric arc lamp, 351
Remanence, 145
Repulsion, electrical attraction and, 20
Residual absorption and charge, 170
Resistance, practical unit of, 43
the B.A. unit of, 44
Lorenz apparatus for determining unit of, 45
variation of, with length, 67
variation of, with cross section, 68
variation of, with material, 68
mass and volume, specific electrical, 69, 70
of conductors, law of, 69
variation of, with temperature, 72
table of specific, 77, 79
laws of magnetic, 136
of a given coil, 160
insulation, 255
and insulation indicator, Everett-Edgcumbe, 256
and length of the electric arc, 349
of cells, internal, 396, 398, 399, 400, 401
Resistances in series and parallel, 83
standard known, 86
standard known, low, 102
Resistivity, 69
Retentivity, magnetic, 11, 145
Ruhmkorff induction coil, 187
Rule for direction of magnetic field and current, hand, 123
for direction of magnetic field and current, needle, 123

Sand blast, 308
Saturation, magnetic, 13
Scale for reflecting galvanometer, 216
Screening, magnetic, 8, 192
Secohm, the, 198
Secondary cells, desiderata in, 412
reactions occurring in, 413
'D.P.,' 415
monobloc, 417
Tudor, 418
chloride, 421
exide, 423
E.P.S., 423
Headland, 425
Edison's alkaline, 425
effect of charging rate on the discharge of, 432
capacity and output of, 432
efficiency of, 434
variation of output with temperature in, 434
effect of method of charging on output and efficiency of, 435
treatment and ailments of, 435
buckling of plates in, 436
purity of acid for, 437
non-corrodible connecting bolt for, 437
uses of, 438
Self-induction, 194
coefficient of, 196
practical unit of, 197
calculation of, 198
Separator for secondary cells, chloride board, 424
Series and parallel circuits, 83
Shunts, theory, ordinary, and universal forms of, 97
Silencing arc lamps, 354
Solenoid, magnetic field and polarity of a, 126
magnetising force of a, 130
Spark coil, Ruhmkorff induction or, 187
Specific magnetic resistance, 14
inductive capacity, 25, 29, 168
electrical resistance, 69
electrical resistance, tables of, 77, 79
conductance, 81
resistance of insulating materials, table of, 107
dielectric hysteresis, 171
gravity with E.M.F., variation of, 428
resistance with density of H_2SO_4, variation of, 428
Spherical candle-power of arc lamp, 382
Spray-arresters for secondary cells, 436
Sprengel air-pump, 323
Standard cell, the Clark, 402
the Weston cadmium, 404
Static hysteresis, 151
Stewart arc lamps, 356
high-economy arc lamp, 359
twin arc lamp, 357
Strength of magnets, 10
Striking the electric arc, 347

Sulphuric acid for secondary cells, purity of, 437
variation of specific resistance with density of, 428
Surface density, 25
Suspensions, pivot and fibre, 216

Temperature coefficient of resistance, 72
of compound circuits, 74
table of, 77, 79
of an electric arc, 347
and output of cells, relation between, 434
Thermal E.M.F., the production of, 385
Thermo-couple, 385
neutral point of a, 386, 389
Thermo-electric diagram, 389
Thermo-E.M.F.'s, laws of, 386
table of, 388
Thermo-pile, 390
generators, efficiency of, 391
Thermometer, electrical, 272
electrical-resistance (Siemens Bros.), 274
indicator, Whipple, 277
Thomson effect, the, 387
Tractive force of magnets, 12
Transient or induced currents, measurement of, 167
or induced currents, quantity of electricity in, 191
Tudor secondary cells, 418
Twin arc lamp, Davy, 355
Stewart, 357

Unit magnetic pole, 17
of electricity, 25
of current, practical, 38
of quantity, practical, 39
of resistance, practical, 43, 45
of resistance, the B.A., 44
of conductance, practical, 46
Unit of potential difference, practical, 49
of work, practical, 53
of heat, 54
of power, practical, 57
of electrical energy, practical, 58
of capacity, 172
of self-induction, practical, 197
Units, the absolute C.G.S. system of, 59
table of electrical, 62
Universal shunts, 99

'V' dry cell, the output of a, 399
Vacuum-gauge (M'Leod), 329
measurement of degree of, 329
Valency, 41, 406
Vapour lamps — (Bastian and Cooper-Hewitt), 337
Velocity, unit of, 60
Viscous hysteresis, 151
Vitrite, 305
Volt, the, 49
Voltaic arc, 345
cell, simple, 393
Voltameters, silver, copper, and mixed gas, 37
Voltmeters, soft-iron needle, 227
vulcan, soft-iron needle, 228
Crompton moving-coil permanent-magnet, 229
hot-wire, 232
electro-static (Ayrton-Mather form), 237

Wattless current, 269
Wattmeter, Hartmann and Braun, 241
Weight, definition of, 51
of a given wire to fill a given coil, 161
Weston standard cadmium cell, 404
Wheatstone bridge, the, 90
the metre form of, 92
the Post Office pattern, 93
Winding of electric magnet coils, 158
Work, definition of, 53, 60

THE END

Printed by R. & R. CLARK, LIMITED, *Edinburgh.*

HARVARD ENGINEERING SCHOOL